NBSIR 73-188

Structural Tests on Housing Components of Glass Fiber Reinforced Polyester Laminate

Thomas W. Reichard, William E. Greene, Jr., Louis E. Cattaneo,
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Center for Building Technology
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Final Report

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U. S. DEPARTMENT OF COMMERCE, Frederick B. Dent, Secretary

NATIONAL BUREAU OF STANDARDS, Richard W. Roberts, Director

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of

Structures, Materials and Life Safety Division
Center for Building Technology

Abstract

This report describes a series of structural evaluation tests performed on housing components made with a glass fiber reinforced polyester (FRP) laminate. The components tested were: 1) The FRP laminate used for the facings and the corrugated core of the basic panel, 2) the adhesive bond between the facing and core, 3) typical wall panels and 4) typical roof panels. Test data include: 1) the effect of temperature and moisture on the tensile and compressive strength of the FRP laminate, 2) the effect of temperature, accelerated aging and sustained loads on the tensile shear strength of the facing-to-core polyester adhesive bond, 3) the short-term strength of the wall panels under compressive and in-plane shear loading, 4) the long-term strength of the wall panels under sustained compressive loading and 5) the short-term and long-term performance of the roof panels under flexural loading.

Key Words: Adhesive bond; Aging; Composites; Compression; Flexure; Glass fiber; Housing system; Innovations; Laminate; Operation Breakthrough; Racking; Reinforced plastics; Reinforced polyester; Sustained loading; Tensile shear.

SI Conversion Units

In view of the present accepted practice in this country for building technology, common US units of measurement have been used throughout this paper. In recognition of the position of the United States as a signatory to the General Conference on Weights and Measures, which gave official status to the metric SI system of units in 1960, assistance is given to the reader interested in making use of the coherent system of SI units by giving conversion factors applicable to US units used in this paper.

Length

1 in = 0.0254 meter (exactly)

1 ft = 0.3048 meter (exactly)

Force

1 lb (lbf) = 4.448 Newtons (N)

Pressure

1 psf = 47.88 N/m^2

1 psi = 6894 N/m^2

Temperature °C = 5/9 (Temperature °F - 32)

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1.0 Introduction

1.1 Objective.

One phase of the Department of Housing and Urban Development's "Operation BREAKTHROUGH" Program was an evaluation of the structural adequacy of each proposed system. The system considered here employs roof and wall sandwich panels constructed from laminated sheets of polyester reinforced with chopped strands of glass fiber (FRP). The basic panel consists of an FRP sheet (facing) bonded to each side of a corrugated FRP sheet (core) with a polyester adhesive.

The structural evaluation process included a consideration of the transfer of stresses through and from the thin FRP sheets into other structural components. To investigate this behavior, tests were performed on wall and roof panels as well as on typical adhesive bonded connections.

1.2 System Description.

Figure 1.2.1 is a schematic of a typical building cross section employing the structural system. The wall and roof panels

are very similar except for overall thickness. The thicknesses shown in figure 1.2.1 are nominal. All wall-to-roof and wall-to-floor connections are made with an epoxy adhesive. The roof is waterproofed with either a factory applied elastomeric coating or a field applied roofing membrane. The exterior surfaces of the walls are normally sprayed with a polymer-aggregate coating for architectural effect. Rock wool insulation is placed in the voids formed by the corrugated cores of the panels. The nominal thicknesses of the FRP sheets are 0.08 in for the facings of the panels and 0.05 in for the corrugated core. The polyester resin content of the FRP sheets was reported by the manufacturer to be 45 percent by weight (approximately 67% by volume). The composition of the polyester resin is not known.

1.3 Scope of Testing.

The testing performed for the evaluation is divided into material property tests and structural component performance tests as follows:

1. The tensile and compressive strengths of the basic FRP laminate and the effects of temperature, humidity and sustained loading on these strengths.

2. The tensile and compressive shear strengths of the facing-to-core polyester adhesive bond and the effects on these strengths of temperature, accelerated aging, and sustained loading.

3. The short-term performance of wall panels under axial compressive in-plane-shear (racking) forces and the sustained loading (creep) performance of the wall panels under an axial compressive force.

4. The short-term and long-term flexural performance of the roof panels.

In addition, an evaluation of the epoxy adhesive bond between the FRP facing and the wood members has been undertaken by another laboratory.[1/] This evaluation is not covered by this report.

2.0 Tests

2.1 FRP Laminate Tests

2.1.1 Scope. Five sheets (each approximately 40 in x 140 in) of the FRP laminate, intended for use as facings in the wall and roof panels, were received from the housing systems producer. Half of each sheet was shipped to the Forest Products Laboratory for testing and the results are reported in [1].[2/] Specimens for the tests reported herein were cut from two of the remaining half-sheets.

Tensile and compressive strength measurements were made on specimens conditioned by three different methods and tested at two different temperatures.

2.1.2 Test Procedure. The tensile test procedure of Federal Test Method No. 406, Method 1011 [2] was used in testing the FRP specimens which had a test-section width of 1.00 in. The compressive test procedure of

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1/ Naval Civil Engineering Laboratory, Port Hueneme, Calif.

2/ Numbers in brackets indicate the references listed at the end of this report.

Method 1021 [2] was used for specimens 0.50 in wide x 3.00 in long. Both procedures are short-term tests. The test conditions were either 73.4°F (23° C) and 50% rh, or 160°F (72°C) and 4% rh.

2.1.3 Conditioning of Specimens. The specimens were cut from the sample sheets after conditioning by one of the following methods:

1. At 73.4°F and 50% rh for 1 week.
2. Soaked in water at 122°F for 48 hours with edges sealed by a mixture of rosin and beeswax.
3. Soaked in water at 122°F for 48 hours with edges not sealed.

The specimens were cut to size then stored for about 2 hours at the test conditions described in 2.1.2.

2.1.4 Test Results. The test results are presented in Table 2.1.1. The average strength values in this table are for sets of 10 specimens and are based on the thickness of each specimen. The thickness of the laminate specimens varied from 0.065 in to 0.107 in with the average being close to the nominal 0.080 in.

The variability in these short-term strength values was so high that the effect, if any, from the water-soak conditioning or the elevated test temperature is not obvious. It was expected that temperature would have an effect on the strength and Boller [1] concluded that the sustained-

load strength of this laminate is considerably less at 160°F than at room temperature. However, he attributed a portion of this loss to the effect of the high humidity (100% rh) which accompanied the elevated temperature.

2.2 Polyester Adhesive Bond Tests

2.2.1 Introduction

2.2.1.1 Objective. A study was initiated to evaluate the polyester adhesive used to bond the corrugated FRP core material to the two FRP laminate sheets used as the sandwich panel facings and to determine the effect on the bond strength of: (1) temperature; 2) adhesive thickness; 3) accelerated laboratory aging: 4) rate of loading; and 5) sustained loading.

2.2.1.2 Scope. Lap joint specimens were tested in tensile shear at various temperatures up to 180°F, at several rates of loading and under sustained loads. Specimens were separated into four groups depending upon the adhesive thickness at the lap joint. Normally, several specimens were tested at each increment of adhesive thickness and temperature, and the average value and the standard deviation computed.

2.2.2 Test Specimens

2.2.2.1 Preparation of Specimens. Test specimens 1/2 in wide and 7 in long were cut from a sandwich panel at the area where the facing was bonded to the nodes of the corrugated core sheet. Notches were cut in the specimens with a band saw in such a way as to provide a lap type, tensile shear specimen with an effective bond area of 0.50 sq in at the lap.

The first eighteen specimens were notched as illustrated by figure 2.2.1 and are referred to in the text as "notch type 1."

Tensile shear tests of these specimens at room temperature resulted in failure in the facing FRP laminate parallel to the adhesive bond. The tensile shear tests of these specimens at 120°F and 180°F produced failure of the polyester adhesive bond to the node of the corrugated core laminate. These results are summarized in table 2.2.1.

To provide additional stability to the FRP laminate during the tests, additional specimens were notched in such a way that notch "A" was made through the core laminate but not through the adhesive. This type of notch will be referred to as "notch type 2" and is illustrated in figure 2.2.2. All specimens tested, except those listed in table 2.2.1, were prepared by the "notch type 2" technique.

2.2.2.2 Specimen Grouping

The polyester adhesive thickness at the bond area of the lap joint in various specimens varied from 0.25 to 5.0 mm. In order to effectively evaluate the adhesive bond the specimens were grouped in the following way: Group A, adhesive thickness less than 1.0 mm; Group B, 1.0 to 2.0 mm; Group C, 2.0 to 3.0 mm; and Group D, 3.0 to 5.0 mm. The highest percentage of specimens was in Group B.

2.2.3 Test Apparatus and Procedures

2.2.3.1 Testing Machine. The tensile shear tests of most specimens were conducted using a testing machine equipped with a temperature chamber shown in figure 2.2.3. The rate at which the load was applied was approximately 300 lb/min. This rate of loading was used in all tests except for the studies of strength versus rate of loading.

2.2.3.2 Sustained Loading Apparatus. Most sustained loading tests were performed with dead weights in place of the testing machine. The dead weight apparatus consisted of 6 individual frames placed on shock absorbent pads in a chamber controlled at 150°F. Each specimen was suspended from a frame and loaded with a bag of lead shot. This apparatus is illustrated in figure 2.2.4. Timer switches were installed under each bag so that the timers were turned off when the specimen failed.

2.2.3.3 Test Conditions. The humidity conditions within the temperature chambers were not controlled but were a function of the laboratory air conditions (73 ± 2°F, 50 ± 2% rh) and the operating temperature of the chamber. Thus, the relative humidity within the chamber varied from about 50 percent at 73°F to 4 percent at 160°F. Specimens with "notch type 2" were tested to determine the minimum test temperature

which would result in adhesive failure to the FRP laminate. Tensile shear tests of twelve specimens at laboratory temperature did not consistently yield failure at the polyester adhesive bond, although three specimens did fail at the bond. As for the other nine specimens--three failed by an internal separation of the outer FRP laminate and six failed as a result of shear of the FRP laminate at notch B. (Figure 2.2.2). The tensile shear results are presented in table 2.2.2. Figure 2.2.5 illustrates the types of failure that were observed. Tests conducted at temperature increments of five degrees from 75° to 110°F indicated that adhesive bond failure could be obtained consistently at 105°F. Therefore, temperatures of 105, 120, 150, and 180°F were chosen for the tests to evaluate the effect of temperature on bond strength.

Specimens were placed in the grips of the machine, which were enclosed in the temperature chamber, before testing. An equilibration time of approximately twenty minutes was used to permit the specimen to reach the chamber temperature before the test was started.

2.2.3.4 <u>Accelerated Aging Procedure</u>. The accelerated aging was ASTM Laboaratory Aging Test C-481, Cycle A [3]. One cycle of the aging consists of the following steps:

1) Total immersion in water at 120 ± 3°F for one hour.
2) Spray with steam and water vapor at 200 ± 5°F for 3 hours.

3) Store at 10 ± 5°F for 20 hours.
4) Heat in dry air at 210 ± 3°F for 3 hours.
5) Spray with steam and water vapor at 200 ± 5°F for 3 hours.
6) Heat in dry air at 210 ± 3°F for 18 hours.

The complete aging procedure consists of repeating the cycle six times and equilibrating the specimens at 73 ± 2°F and 50 ± 2% rh to constant weight. The tensile shear tests were carried out at temperatures of 73, 105, 120, 150 and 180°F immediately following the equilibration period.

2.2.4 Test Results

2.2.4.1 Bond Strength Versus Temperature. Approximately seventy specimens were tested in tensile shear at temperatures of 105, 120, 150, and 180°F. The failure for all specimens was in the polyester adhesive bond to the node of the corrugated core FRP laminate. The results of these tests are presented in table 2.2.3.

The effect of increasing temperature on the adhesive bond strength was extracted from tables 2.2.2 and 2.2.3 and is illustrated in figure 2.2.6. The adhesive bond strength decreased significantly with increasing temperature with the bond strength at 180°F averaging about 25 percent of the strength at 73°F. The point on each curve at 73°F represents a less-than-maximum bond strength at that temperature since the FRP laminate failed in most room temperature tests. The adhesive was observed to be more pliable at elevated temperatures than at room temperature.

2.2.4.2 Bond Strength Versus Adhesive Thickness. Figure 2.2.7 is a graph of polyester adhesive bond strength versus adhesive thickness. The data for these curves were extracted from Table 2.2.3. This graph indicates that the adhesive bond strength decreased significantly with increasing adhesive thickness. Decreasing strength with increasing adhesive thickness has been noted in a previous study [4].

2.2.4.3 Bond Strength After Aging. Sixteen specimens with "notch type 2" were subjected to the ASTM Laboratory Aging Test, C-481, Cycle A, before obtaining bond strength values at temperatures of 73, 105, 120, 150 and 180°F. The resulting bond strength values are summarized in table 2.2.4. Table 2.2.5 contains a comparison of the average values obtained in the tests with and without laboratory aging. This comparison indicates that the accelerated aging did not significantly reduce the bond strength of the polyester adhesive. The values at 73°F were again indicative of FRP laminate failure rather than adhesive bond failure.

2.2.4.4 Bond Strength Versus Rate of Loading. Additional samples with "notch type 2" were tested in tensile shear at various loading rates and the data obtained are presented in table 2.2.6. The data from samples requiring approximately 0.4 minutes to fail were extracted from table 2.2.3. Figure 2.2.8 graphically illustrates the data in table 2.2.6 for Group B. The data for other groups provide similar curves.

The data obtained from Group B samples at 150°F were plotted by the modified Prot method [5, 6, 7] described by Boller [6]. The results indicate that the change

in failure load with rate of loading is too large for the Prot method to be applicable to this particular system.

2.2.4.5 Bond Strength Under Sustained Loading. Thirty-two Group B (1.0-2.0 mm adhesive thickness) specimens were tested at 150°F with sustained loads in tensile shear to determine the endurance limit. Sustained loads of 100, 60, 50 and 40 lbs were applied with the testing machine. Other sustained loads of 40, 35, and 25 lbs were applied by suspending the lead shot weights from the specimens. All failures observed were in the polyester adhesive bond to the core FRP laminate. The data obtained are presented in table 2.2.7. Figure 2.2.9 is a graph of the sustained load versus time to failure. Three specimens were tested in the sustained load apparatus at 35 lb and three at 25 lb. One specimen loaded at 35 lb failed at 296 hours and one specimen loaded at 25 lb failed at 728 hours. The other two specimens at each of these loads exhibited no failure at 3000 and 3500 hours, respectively. Extrapolation of the curve of figure 2.2.9 to 10,000 hours yields an endurance limit of 30 lbs (60 psi).

2.2.5 Discussion of Polyester Adhesive Bond Tests. When interpreting the bond test results of this report, it should be remembered that the test specimens were specially made for these tests and that quality control factors used in fabricating the panel material are variables which were not included in this study. The strength of these bonds would be significantly affected by fabrication and handling practices as well as by the type and composition of the materials. The quality

control factors critical to the strength and durability of the adhesive bond include the quality of the substrates (FRP sheets); the condition of the substrate surfaces (contamination, moisture, temperature, porosity, etc.); the composition and mix proportions of the adhesive; age at application and pot life of the mixed adhesive; time, temperature and humidity during the curing process; and the age of the bond when panel is loaded.

The bond test results presented in this report (Fig. 2.2.7) show that the thickness of the adhesive is a significant quality control factor. For this panel material in which the quantity of adhesive per unit length of bond is a constant (gun applied) the thickness of the adhesive in the joint affects the bond area, the bond strength and the stress level. Thus, in a thicker adhesive joint the bond area will be smaller, the bond strength will be lower, and the stress level will be higher. For the panel materials tested for this report the width of the bond between the FRP facings and the core nodes usually varied from 1/2 in to 1-1/2 in, but at a few bond areas the width was considerably less than 1/2 in.

These bond test results also clearly indicate that the results from short-term tests at ordinary laboratory conditions are insufficient when estimating the expected service performance of such panel material. This is especially true for roof panels where the temperature and humidity within the panel can reach 160°F and 100 percent relative humidity and where appreciable loads must be sustained for extended periods of time.

The data shown in figure 2.2.6 are especially pertinent for roof panels because of the indication that the short-term bond strength for this polyester adhesive at 160°F is only about 1/3 as high as it is at 73°F.

Boller's data [1] for sustained loading under 100 percent relative humidity on specimens cut from the same panels indicate a significantly greater loss of bond strength than the data of figure 2.2.9 which was for sustained loading under low humidity conditions. These data indicate that high humidity degrades the bond strength over and above the effect of the sustained loading and elevated temperatures. Furthermore, Boller's data also indicate a reduction in the bond strength with aging. His procedure (ASTM C481) is the same as was used in developing the data of tables 2.2.4 and 2.2.5 which indicate no significant effect from the aging. However, Boller's data are considered to be more reliable because of the larger number of specimens.

In conclusion, these results indicate that the sustained shear stress in the polyester adhesive bond of the roof panels identical to those tested should not exceed 5 psi. Because of the variability in the bond area the shear stress in the bond of a typical roof panel can only be approximated, and so, when computing design stresses this variability should be considered. The long-term effect of high humidities on the strength of these polyester adhesive bonds is probably very significant, but was not fully investigated. Additional testing is being performed on this effect, but some development work is needed towards improving the long-term reliability of the bond between the FRP facing and core.

2.3 Wall Panel Tests

2.3.1 Introduction. The purpose of this part of the physical testing program was to evaluate the performance

of wall panel specimens under the action of racking loads and of short-term and long-term compressive loads. In service, wall panels receive such loads from the tributary areas of floors and roofs supported by them and from other in-plane or transverse walls. Such cumulative loads were simulated in separate static tests to determine the short-term and long-term load carrying capacities of the wall panels. Five wall panels were tested: one in racking, two in short-term compression and two in long-term compression.

Wall panel specimens were fabricated by the housing system producer and were ready for testing when received. Panels were typical of those intended for use in the building system, but did incorporate some additional wood members at the top and bottom edges to facilitate test simulation of service loading. These additional wood members were judged to provide a satisfactory simulation of the in-service load distributing surfaces (floor and roof) without unduly reinforcing the wall panel specimens. A wall panel specimen consisted of two thin facings made of the FRP laminate separated by a vertical stiffening core which was a corrugated sheet of the same material (Fig. 2.3.1). The corrugated core was bonded to the two facings with a polyester adhesive. Each test panel contained a 2 x 4 (1-1/2-in x 3-1/2-in) wood top plate and sole plate. These wood members were bonded to the facings with an epoxy adhesive and were completely within and flush with the top and bottom edges of the FRP facings. Examination after the tests showed that the wood plates did not touch the ends of the core corrugations. The additional wood members attached for test purposes to the top and bottom of each panel are described below.

In order to obtain engineering data on the wall panels in a generally recognized manner, test methods for determining short-term compressive and racking characteristics followed ASTM Designation E72-68 [8]. Wherever techniques or equipment differed from E72 recommendations, they are described in the appropriate sections below. All load-displacement measurements in short-term tests were recorded automatically on magnetic or punched paper tape for computer processing.

2.3.2 Racking Tests

2.3.2.1 Test Specimen. One specimen of wall panel construction was tested in a normal vertical position by subjecting it to horizontal racking forces. The specimen was 7 ft-1 1/2 in wide by 8 ft (nominally) high by 3-7/8 in thick. (See Fig. 2.3.1). The 96-in height of the panel proper was increased by two 2 x 4's nailed and adhesive bonded (flat-wise) along the top edge and the bottom edge of the panel. These attached members (See section C-C of fig. 2.3.1) were intended to distribute the racking load and its reaction horizontally along the top and bottom edges of the test panel. The entire specimen consisted of two narrower panels connected by the producer. This connection had been made by polyester adhesive bonding external FRP joint cover plates to the individual panel facings (See section B-B of fig. 2.3.1).

2.3.2.2 Test Apparatus and Procedures. The loading apparatus, assembled as shown in figures 2.3.1, 2.3.2, and 2.3.3 for three different test

arrangements, consisted of 30-ton hydraulic rams attached to a structural steel framework connected to the laboratory tie-down test floor. The specimen was bolted and clamped (by the two bottom 2 x 4's) between steel channels which, in turn, were bolted to the test floor. A toe stop connected to the floor was also used to prevent sliding of the specimen under horizontal load. Lateral guides were provided in the form of caster wheels mounted on rigid steel plates and applied to the sides of the panel top at mid-length. Additional vertical hold-down of the specimen in the second and third tests was accomplished by hydraulic rams attached to the test frame. All ram loads were applied through roller bearings (Fig. 2.3.4) and were measured to the nearest 10 lb by an electric strain gage pressure transducer which had been calibrated in combination with the rams. Panel displacements and deformations were measured by electric displacement transducers (linear variable differential transformers--LVDT) to the nearest 0.0001 in. The LVDT's, which measured panel deformation, were mounted in aluminum tubes and pin-connected to the wall panel (using a hot-melt adhesive) as shown in figures 2.3.3 and 2.3.4. Diagonal gage lengths were 118.25 in, vertical gage lengths were 88.88 in, and horizontal gage lengths were 78.63 in. The LVDT's, which measured wall panel displacements at the outer extremities of the panel, were mounted on rigid stands resting on the test floor. Three racking tests were performed on the one specimen by re-setting the specimen between tests. In all tests the racking load was applied in increments of 1000 lb.

In the first test (Fig. 2.3.1) the racking load was increased monotonically until an indication of impending failure was observed. No vertical hold-down from above the wall was supplied in this test in order to allow possible rotational failure to develop at the bottom. Upon application of each successive load increment, displacements were measured and recorded.

In the second test the racking load was applied incrementally and reduced to zero after each additional increment was applied. The racking load was increased until failure developed. Additional vertical hold-down was supplied at the loading corner by a hydraulic ram which was loaded to maintain the specimen in static rotational equilibrium. (Fig. 2.3.2).

The third test was conducted in the same manner as the preceding test except that the vertical hold-down above the wall was provided by six equally spaced rams operated simultaneously by a common pump. The vertical resultant of these rams was always such as to maintain the specimen in static rotational equilibrium. (Fig. 2.3.3).

2.3.2.3 Racking Test Results. The first test was conducted without the vertical hold-down recommended in ASTM Method E-72 in an effort to evaluate the performance of the bond between the FRP panel facings and the wood sole plate. However, the test was terminated at a maximum total racking load of 5700 lb (800 lb/ft) beyond which the load could not be increased. The failure which prevented greater load development occurred in the bond between the two

extra bottom 2 x 4's with no apparent damage to the FRP facing bond. Figure 2.3.5 shows the failure at the bottom trailing corner (heel) of the specimen where uplift was being measured. The graph of figure 2.3.6 shows the relationship between racking load and net horizontal drift (corrected for uplift and sliding); and between racking load and rotational uplift for test No. 1.

After re-setting and re-clamping the bottom edge of the wall, the second test was performed in the manner of ASTM Method E72; i.e., with vertical restraint provided at the loading corner. The maximum total racking load which could be developed was 7200 lb (1010 lb/ft). The observed failure was in the epoxy adhesive bond between the FRP facings and the top plate at the loading corner of the specimen (Fig. 2.3.7). Figure 2.3.8 shows racking load versus net drift under load; and versus net residual drift (set) measured at no-load upon removal of each incremental load. Note that the dotted portions of the curves represent the concluding part of this test in which displacement readings are considered unreliable. The apparent stiffening (reduction of displacement with increase in load) is attributed to the development of greater distortions at locations on the specimen other than those instrumented.

The third test which employed a vertical hold-down distributed along the top of the wall (instead of the ASTM E72 hold-down), developed a maximum total racking load of 6800 lb (950 lb/ft). The failure was in the epoxy adhesive bond between the FRP facings

and the wood sole plate at the bottom leading corner (toe) of the specimen (Fig. 2.3.9). Measured observations of drift (as described for the preceding test) are shown for test No. 3 in figure 2.3.10.

In addition, the sequence of figures 2.3.11, 2.3.12, 2.3.13 shows for each test, the relationship of racking load to extension and to shortening in the major diagonals of the wall panel. Transducer measurements made over the horizontal and vertical gage lengths of the specimen were not considered significant and, consequently, are not reported.

2.3.3 Short-Term Compressive Tests

2.3.3.1 Test Specimens. Two specimens of wall panels were tested in axial compression. Each specimen was 40 in wide by 96 in (nominal) high by 3-7/8 in thick (Fig. 2.3.14). In addition to the 96-in height (used as reported height of test specimen), each specimen had two 2 x 4's nailed and adhesive bonded (flatwise) along the bottom edge of the panel. In addition, along the top edge of each specimen, there was nailed and adhesive bonded (to the wall panel top plate and to each other) one 2 x 4 on edge beside one 2 x 2 (1-1/2 in x 2 in) as shown in section B-B of figures 2.3.14. The additional members at the bottom and top were intended to simulate the bearing conditions at the portions of the floor and ceiling to which the wall panel would be attached.

2.3.3.2 Test Apparatus and Procedure. Tests were performed in a 600,000-lb compression testing machine (as shown in figure 2.3.14) following ASTM Method E72. Specimens were positioned vertically in the machine so that the line of load application was centered on the 1-1/2-in side of the upper 2 x 4 resting on edge. This resulted in a load eccentricity of 1 in (i.e., an eccentricity ratio, or fraction of panel thickness, equal to 0.26).

Each panel was tested as a column having a flat end at the bottom and bearing on a steel plate which rested on the platen of the testing machine. Loads were applied along the top end through a 3/4-in x 2-in steel plate on which rested a 3/4-in half-round steel bar with the flat side toward the wall. A 6-in WF beam transmitted the load from the testing machine head to the assembly described above. The tare weight of the above loading fixtures (111 lb, i.e., 33 lb/ft) was not included in recorded load observations. The loading rate corresponded to a testing machine crosshead movement of 0.03 in/min.

Vertical wall shortening measurements were made by four compressometers made of LVDT's mounted in aluminum tubes attached to the faces of the wall panels near the four vertical edges. Tubes were pin-connected to the panel at the top. The compressometer gage lengths were 92 in. Locations of compressometer attachment were chosen to coincide with locations of the facing-corrugation junctions nearest to the edges of the wall. These locations were chosen in order to have the compressometers

mounted on braced skin areas to avoid regions which might possibly buckle prematurely. Distances of the compressometers from vertical wall edges ranged from 4 in to 8 in. Locations of the facing-to-corrugation junctions were determined by observing the shadows produced by a flood light projected through the translucent wall structure. In order to aid visual detection of skin buckling during the test, ink lines were drawn on the panel faces horizontally at intervals of 12 in, and vertically at locations midway between facing-to-corrugation junctions (intervals of about 6 in $\pm$ 1 in).

Lateral deflections were measured with two LVDT displacement transducers. Each was mounted transversely at the middle of a 92-in aluminum tube which was pin-suspended at the top end along the mid-thickness of a wall edge. The bottom ends of these tubes were attached with rubber bands to guides fastened to the wall on the thickness centerline which permitted the tubes to slide as the wall shortened under load. Lateral deflections and wall shortening displacements were measured to the nearest 0.001 in.

In addition, measurements of vertical strain were made at the centers of both surfaces of the wall panels by use of 6-in electrical resistance strain gages.

Compressive load was applied to the specimens in increments of 500 lb and reduced to a holding load of 500 lb after each incremental increase. Deformations measured by all transducers were recorded at each

incremental load increase and at the subsequent reduction to the holding load. This observation of load deformations and residual deformations was continued beyond the wall panel design ultimate load to a value of 2100 lb/ft. Beyond this point the specimens were loaded monotonically up to their ultimate load carrying capacity.

In test No. 1 stops were made in the upper loading range at intervals of 5000 lb to observe and record deformations; instruments were removed when impending failure became apparent. Later examination of this data indicated jamming of instruments near the 10,000 lb load. Instruments in test No. 2 were removed after unloading from 7000 lb (2100 lb/ft).

2.3.3.3 <u>Test Results</u>. The two short-term compressive specimens were used for duplicate tests. The first specimen sustained a maximum compressive load of 20,800 lb (6240 lb/ft) and the second specimen, 19,750 lb (5925 lb/ft). Failure in the first specimen occurred in the epoxy adhesive bond between the FRP facing and the wood sole plate on the side closer to the eccentric load (Fig. 2.3.15). In the second specimen a similar failure occurred in the epoxy adhesive bond between the FRP facing and the top plate on the side closer to the load (Fig. 2.3.16). Subsequent to these bond failures, secondary failures occurred in both specimens when the facings buckled near the bond separations.

Figures 2.3.17 and 2.3.18 show development of average-shortening (4 transducers) in the two specimens with increasing load. Residual deformations were

measured at a small holding load of 500 lb (150 lb/ft). Figure 2.3.19 shows the average deflections (2 transducers) developed in 92 inches of specimen length by the loading sequence of test No. 1. The negative deflection shown in this graph was probable accommodation of instruments upon application of the initial load. Figure 2.3.20 shows the deflections measured at only one side of the specimen in test No. 2. The second transducer was used for monitoring the test by an X-Y recorder; the record was not satisfactory for reproduction.

Figure 2.3.21 illustrates load versus mid-height surface strains of both faces of the specimen for test No. 1 as measured with the electrical resistance strain gages.

2.3.4 Long-Term Compressive Tests

2.3.4.1 Test Procedure. Two wall specimens identical to those described in 2.3.3.1 above were tested under a sustained load of 6000 lb (1800 lb/ft). The load was applied along the center line of the upright 2 x 4 member as was described in 2.3.3.2.

Two different support conditions were included. The first condition was the ASTM E-72 flat bottom support and is illustrated in figure 2.3.22. The second condition was with the bottom supported on a roller to provide the same eccentricity as at the top. This second support condition is shown in figure 2.3.23. These figures also show the springs used to sustain the load as well as the taut wire and mirrored scale used for measuring the deflection.

Both wall specimens were originally loaded with the flat bottom support. After 24 days a single specimen was reloaded with the eccentric bottom support.

2.3.4.2 <u>Test Results</u>. With the flat bottom support, specimen No. 1 failed after 18 days under the 6000-lb (1800 lb/ft) sustained load. Failure was due to loss of epoxy adhesive bond between the 2 x 4 sole plate and the FRP panel facing. This bond failure allowed the wall to rotate on the flat bottom support until the 2 x 4 sole plate rested on the corrugated core of the wall. This mode of failure was the same as described in 2.3.3.3 for the short-term compressive test.

Specimen No. 2 had also been loaded with the flat bottom support, however, after 24 days under 6000 lb of sustained load it did not show any sign of failure. Specimen No. 2 was then unloaded and reloaded to 6000 lb with the eccentric-bottom support. After 53 days under these conditions specimen No. 2 failed in an identical manner as specimen No. 1. Figure 2.3.24 is a photograph of the bottom end of this specimen after failure. Failures in both specimens were gradual; i.e., there was a slight rotation at the sole plate several days before the epoxy adhesive bond broke loose for the full width of the specimen.

Figure 2.3.25 is a plot of the midheight deflection versus time-under-load for the three tests. Near

failure, the measured deflection was less than the correct value because the rotation of the sole plate moved the taut-wire attachment point in the direction that reduced the measured value.

2.3.5 Discussion of Wall Panel Test Results. Probably the most significant observation made during the wall panel tests was the common mode of failure: i.e., separation of the FRP facing from the top or bottom 2 x 4 wood plates at the epoxy adhesive bond. Since there is a gap (as much as 1/4 in) between the corrugated core and these wood plates (see section C-C, figure 2.3.1) all forces acting on a wall must be transferred through this epoxy adhesive bond. This method of transferring forces precluded the development of the full-potential of this type of structural sandwich.

The data from these wall panel tests were interpreted in the absence of data needed to reflect the effects of aging, environmental conditions, and variability on this epoxy adhesive bond. The effects of these factors on the sustained-load strength of this bond are being studied by others (see footnote 1, page 3). If, in considering variability, a conservative value of 0.4 is assumed as the coefficient of variation (ν), the observed load capacities should be adjusted by a factor of $(\frac{1}{1 + 1.5\nu})$ which is equal to 0.625[3/]. When this factor is applied, the racking load capacity of the panels is reduced to 600 lb/ft. However, this will probably be reduced

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[3/] Assuming a normal distribution, with known mean and standard deviation, the requirement that structures be designed for an overcapacity of $(1 + 1.5\nu)$ times the required capacity would mean that approximately 95 percent of that population of structures would have at least the factored load capacity.

further when data for aging and environmental effects become available. Similarly, the factored short-term compression load capacity of the wall panels becomes 3800 lb/ft. Unlike racking loads which are usually of short duration (e.g., wind) gravity compressive loads often exist for prolonged periods. The rated capacity in compression will, therefore, be governed by the long-term test data (which will also be modified by pending test data for aging and environmental effects). Projection of the data in figure 2.3.25, together with factoring for variability indicates that a long-term bearing load should not exceed 830 lb/ft of wall. This is based on the judgement that a proportionately smaller load will produce in a period of 50 years a deflection equal to that displayed by the test specimens at incipient failure. Again, the calculated estimate was reduced by the conservative variability factor of 0.625.

All evidences of failures in the wall tests point toward the need for improvement in fabrication methods at the top and bottom of wall panels. In addition to improving the adhesive bond between FRP facing and the 2 x 4 wood plates, the gaps between the corrugated cores and the wood plates should be eliminated in order to improve the transfer of loads throughout the panel.

2.4 Roof Panel Tests

2.4.1 Introduction. The evaluation of the performance of roof panel specimens when subjected to short-term and long-term loading constitutes the purpose of this part of physical testing program. Service gravity loads for roofs result from snow, rain, sleet, hail, and from the workmen

who construct and repair roofs. Long-term loading represents some portion of the short-term load that is considered to remain on a roof for an extended period of time. These loads were simulated in separate static tests to determine: (1) deflection under loading which might be encountered in service, (2) the overload capacity, and (3) deflection under long-term loading. Two specimens were tested, one for service loading and overload capacity, and one for deflection under long-term loading.

2.4.2 Test Specimens. The two roof specimens received for testing consisted of flat panel sections, 3 ft- 4 in wide by 12 ft long. The panels were a sandwich composite fabricated by bonding the FRP laminate facings to a 5 3/4 inch deep corrugated FRP laminate core with the polyester adhesive. The ends of the facings were bonded with an epoxy adhesive to wood closure assemblies which were fabricated from nominal 2-inch thick (1-1/2 in actual) framing lumber, as shown in figures 2.4.1, 2.4.2 and 2.4.3. The latter figure indicates that the core is not connected to the closure assemblies, therefore, the shear load path is through the top and bottom facings and the closure assembly to the supporting walls.

2.4.3 Test Apparatus and Procedures.

2.4.3.1 Short-Term Flexural Tests. The loads for the short-term flexural tests were applied by the use of air bags. This was accomplished by placing the roof specimen upside down, approximately 2 inches above the laboratory floor, with an air bag between the specimen and the floor. The roof panel was supported at one end by a rocker and at the other end by a roller.

LVDT's were attached to the test specimen to monitor midspan deflection and end rotation. Figures 2.4.4 and 2.4.5 illustrate the test setup. The deflections indicated by the two exterior LVDT's located at midspan were plotted by X-Y recorders. This provided a real-time record of midspan deflection versus pressure. The readings taken from the remaining LVDT's were recorded on paper tape. A schematic diagram of the instrumentation and recording equipment is presented on figure 2.4.6.

The air bag pressures required to simulate serviceability and safety loading were adjusted to include an allowance for the inability to load the entire panel surface. This adjustment was required due to weak longitudinal panel edges, and also, as the panel deflects, to some further reduction of area as a result of the increase of radius in the air bag at the longitudinal edges of the panel. The latter situation was found to be of secondary importance for this specimen. A total width reduction of 8 inches was used to calculate the test pressures. This was later checked by taking measurements from the edge of the panel to the edge of the contact area at the safety loading pressure, which was found to be approximately 7.75 in.

To insure that the ends of the panel were free to rotate, a gap was provided between the reaction beams and the end support assemblies as shown on 2.4.4. Before starting the test, the air bags were pressurized to approximately 5 psf (the panel dead load) to seat the end supports against the reaction beams. Further

pressurization constituted the test loading.

The service load was applied and relaxed three times to check for linearity and residual deflection. The loading for structural safety however, was applied only once.

2.4.3.2 Long-Term Flexural Tests. To simulate this condition, one panel was loaded to 5 psf with the appropriate depth of sand. Although the entire surface area of the panel could not be loaded because of the unsupported facing edges, the total panel load was achieved by increasing the depth of sand on the reduced area. Wood slats three inches long were glued on the panel surface along the centerline of the outermost core corrugation to contain the sand. To avoid increasing the structural stiffness of the panel, 1/8 inch gaps were left between the retaining slats. These gaps were later covered with masking tape to prevent sand leakage. Sand was then placed on the panel and screeded to the top of the slats which had been milled to the required height of 0.8 in. Figure 2.4.7 is a picture of the roof panel under long-term sustained load test and figure 2.4.8 illustrates the test apparatus and arrangement. To simulate simple support end conditions, a rocker and a roller were used as illustrated in figure 2.4.4.

Two deflection gages, located at midspan, were read and recorded daily for the first two weeks; thereafter readings were taken and recorded weekly. Temperature and humidity were also recorded at the time of the deflection readings.

2.4.4 Test Results.

2.4.4.1 Short-Term Test Results. The results of this test are expressed in the form of load versus midspan deflection plots which are presented in figures 2.4.9 and 2.4.10. Figure 2.4.9 is a typical example of one of the three cycles of serviceability loading (20 psf live load + 5 psf dead load) which were performed. Figure 2.4.10 is a plot of the ultimate load test. The roof panel was not loaded to its ultimate, however, because the air bag failed first. At this point the load on the roof panel had exceeded the recommended ultimate load (65 psf) by a factor of 1.8.

2.4.4.2 Long-Term Test Results. The results of this testing are presented on figure 2.4.11. Midspan deflections, temperature and humidity readings were taken for 280 days but only the first 100 days of the test period are considered usable because a failure in the temperature and humidity control unit resulted in erratic environment conditioning after this initial period. The data points for days 12 to 100 plot approximately as a straight line when time is plotted on a logarithmic scale. If this line is extrapolated to 50 years, the calculated deflection is 0.35 inches. This deflection, when added to the instantaneous deflection caused by a live load of 20 psf, which was determined to be 0.21 in, yields a total deflection of 0.56 in for a simulated long-term loading condition.

2.4.5 Discussion of Roof Panel Tests

2.4.5.1 Short-Term Tests. The load/deflection plots shown in figures 2.4.9 and 2.4.10 indicate that the structural behavior of the roof panel tested is

linear and, presumably, elastic up to a load of approximately 80 psf. The assumption of elasticity is further reinforced by the fact that the apparent residual deflection indicated for the simulated service loading (Fig. 2.4.9) would recover to within 0.01 in. in a few hours after the load was removed. This delayed recovery behavior is common to many structural systems fabricated from FRP materials.

The loads imposed on the roof panel to simulate service and ultimate loading were 20 psf and 65 psf, respectively. The first value is consistant with service loads which are specified in a large number of building codes in the United States for single and multiple dwelling flat roofs. The ultimate load values, although not usually directly specified, would exceed most building code requirements for safety factors against failure. Most codes also limit the midpoint deflection of a roof under service load conditions. A common value in current use is 1/360 of the span or 0.33 in for this case. The measured value (see fig. 2.4.9) was 0.21 in for a live load of 20 psf.

2.4.5.2 Long-Term Tests. Most current U.S. codes covering residential construction do not have specific requirements for long-term loading because they are oriented toward the use of conventional structural materials such as wood, concrete, masonry and steel. The lack of a specific requirement in this area probably stems from the knowledge that the durability of conventional materials, when properly protected, will generally exceed the useful life of the building. However, when unconventional materials and structural systems are used for residential

construction, some attempt at evaluating the behavior of such structures over a long period of time must be made. This was done by extrapolating the data for 50 years as described in section 2.4.4.2, and resulted in a calculated midspan deflection of 0.56 in. This deflection is slightly less than 1/240 of the span, which is the maximum allowed by many codes for roofs subjected to short-term loads of 1 dead plus 1 live.

3.0 Summary and Conclusions

This report describes a series of structural evaluation tests on housing components made with a glass fiber reinforced polyester (FRP) laminate. The components tested were: 1) The FRP sheet laminate used for the facings and corrugated core of the basic panel, 2) the polyester adhesive bond between the facing and core, 3) typical wall panels and 4) typical roof panels. Test data include: 1) the effect of temperature and moisture on the tensile and compressive strength of the FRP laminate, 2) the effect of temperature, accelerated aging and sustained loads on the tensile shear strength of the facing-to-core polyester adhesive bond, 3) the short-term strength of the wall panels under compressive and in-plane shear loading, 4) the long-term strength of the wall panels under sustained compressive loading and 5) the short-term and long-term performance of the roof panels under flexural loading.

The test data presented in this report indicate the following conclusions:

1.) Water-soaking at 122°F for 48 hours and/or testing at 160°F had no significant effect on the tensile strength of the FRP laminate.

2.) The temperature and thickness of the polyester adhesive had a significant effect on the tensile shear strength of the bond between the FRP laminate facing and core. The short-term bond strength at 160°F was only about one-third of the strength at 73°F. The short-term bond strengths in specimens with an adhesive thickness of 3 to 5 mm was only about half of those with an adhesive thickness of 1 mm or less. The variability in adhesive thickness, which is a quality control factor in fabrication, must be considered in the design of such panels.

3.) The shear strength of the bond was much less under sustained loading than under short-term loading.

4.) Accelerated aging by ASTM C-481 had no significant effect on the polyester adhesive bond strength. However, Boller's data [1] for the same material indicate that high humidity will significantly reduce the bond strength.

5.) Failures in the wall panels under short-term and long-term compressive loading and under short-term in-plane shear loading were in the epoxy adhesive bond between the FRP facing and the 2 x 4 wood plate.

6.) The long-term edgewise compressive strength of the wall panel was less than one-third of the short-term strength.

7.) The performance of the roof panel would satisfy building codes with a requirement for a live load of 20 psf.

8.) The effects of quality control variables and of high humidity for extended periods on the performance of these panels were not fully evaluated. However they are considered to be highly significant factors.

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Table 2.1.1 FRP Laminate Test Results

Sheet No.	Conditioning Prior to Test	Test Conditions Temp.	Test Conditions RH	Compressive Strength Average	Compressive Strength High	Compressive Strength Low	Tensile Strength Average	Tensile Strength High	Tensile Strength Low
		C	%	psi	psi	psi	psi	psi	psi
1A	23C, 50% rh	23	50	18,400	23,300	11,600	8,800	10,600	8,300
		72	4	--	--	--	9,200	10,300	8,300
	48 hr. in 50C water. Edges sealed.	23	50	15,800	17,700	12,200	10,200	11,300	9,100
		72	4	--	--	--	8,900	10,400	7,000
	48 hr. in 50C water. Edges not sealed.	23	50	14,400	16,500	10,000	8,500	9,400	7,200
		72	4	--	--	--	7,400	8,700	5,700
2A	23C, 50% rh	23	50	19,900	23,000	15,300	10,700	11,900	8,500
		72	4	--	--	--	11,100	11,800	9,100
	48 hr. in 50C water. Edges sealed.	23	50	16,900	21,200	14,200	10,700	14,000	9,200
		72	4	--	--	--	8,600	11,300	7,500
	48 hr. in 50C water. Edges not sealed.	23	50	19,000	21,300	14,600	8,500	9,400	7,200
		72	4	--	--	--	9,100	10,200	7,300

Table 2.2.1 Preliminary Polyester Adhesive Bond Test Results Using Specimens with Type 1 Notch (Tensile Shear Test)

SPECIMEN NUMBER	ADHESIVE THICKNESS	TEST TEMP	MAXIMUM LOAD	TYPE OF FAILURE
	mm	^{o}F	lbs	
1-1	2.0-2.5	73	182	Delamination within facing laminate parallel to bond
2-1	2.0	73	132	"
4-1	2.5-3.0	73	161	"
11-1	2.0	73	176	"
16-1	1.0	73	165	"
18-1	1.25-1.50	73	195	"
8-1	2.5	120	130	Adhesive bond to core laminate
9-1	2.0-2.5	120	135	"
10-1	2.0	180	101	Adhesive bond to core laminate
13-1	1.5	180	126	"
17-1	1.5-1.75	180	73	"

Table 2.2.2 Polyester Adhesive Bond Test Results at 73°F Using Specimens with Notch Type 2 (Tensile Shear Test)

SPECIMEN NUMBER	ADHESIVE THICKNESS	MAXIMUM LOAD	TYPE OF FAILURE
	mm	lbs	
1-2	2.5-4.0	171	Adhesive bond to core laminate
2-2	2.0-3.0	115	"
3-2	2.5	213	"
19	1.0	220	Tensile failure in core laminate at Notch B
10	1.5	305	Delamination within facing laminate parallel to bond
12	1.5-1.75	264	Tensile failure in core laminate at Notch B
13	1.0-2.5	237	"
15	2.0	168	"
9	2.0-2.5	283	"
4	3.5-4.0	154	"
157	0.5-1.25	*284	Delamination within facing laminate parallel to bond
187	0.75	351	"

*Some weakening in laminate noted before test.

Table 2.2.3 Polyester Adhesive Bond Test Results at Various Temperature Using Specimen With Notch Type 2

GROUP A (<1.0 mm) 1/				GROUP B (1.0-2.0 mm) 1/				GROUP C (2.0-3.0 mm) 1/				GROUP D (3.0-5.0 mm) 1/			
SPECIMEN NUMBER	ADHESIVE THICKNESS	TEST TEMP	MAX LOAD	SPECIMEN NUMBER	ADHESIVE THICKNESS	TEST TEMP	MAX LOAD	SPECIMEN NUMBER	ADHESIVE THICKNESS	TEST TEMP	MAX LOAD	SPECIMEN NUMBER	ADHESIVE THICKNESS	TEST TEMP	MAX LOAD
	mm	°F	lbs		mm	°F	lbs		mm	°F	lbs		mm	°F	lbs
				36	1.5	105	162	26	2.5	105	132	22	3.0-3.5	105	119
								43	3.0	105	101				
				37	1.5	105	185	49	2.5	105	162	39	3.5	105	95
				33	1.0-1.5	105	133	66	2.0	105	134	42	3.0-3.5	105	98
				62	1.5	105	164	73	2.0	105	136				
				63	1.5-1.75	105	157	74	2.5	105	138				
				64	1.5-2.0	105	171	75	2.5	105	135				
							($\bar{X}$=162±16) 2/				($\bar{X}$=134±17) 2/				($\bar{X}$=104±12) 2/
159	0.75	120	220	11	1.5	120	154	6	2.5	120	116	2	4.0-4.5	120	74
160	0.25-0.75	120	242	17	1.5-2.0	120	149	24	3.0	120	122	5	4.0	120	96
188	0.50	120	230	34	1.0-1.5	120	104	46	3.0	120	126	23	3.5	120	90
				35	1.5-2.0	120	119	48	2.5-3.0	120	106	44	3.0-3.5	120	78
				68	1.5-2.0	120	154								
				69	1.5-2.0	120	168								
				70	1.0-1.5	120	167								
				71	1.5-2.0	120	167								
				72	1.5-1.75	120	171								
			($\bar{X}$=231±11) 2/				($\bar{X}$=150±23) 2/				($\bar{X}$=118±9) 2/				($\bar{X}$=85±10) 2/
161	0.5-1.0	150	146	57	2.0	150	106	51	3.0	150	63				
177	0.75-1.0	150	140	58	2.0	150	133	55	2.5-3.0	150	73				
189	1.75	150	150	60	2.0	150	106	56	2.5	150	53				
								59	2.0-3.0	150	80				
			($\bar{X}$=145±5) 2/				($\bar{X}$=115±16) 2/				($\bar{X}$=67±12) 2/				
178	0.75-1.0	180	92	8	1.75	180	80	3	3.0	180	55	1	4.5-5.0	180	42
190	0.5	180	87	16	2.0	180	74	7	2.5	180	78	40	4.0	180	48
				18	1.75	180	70	25	2.75	180	45	41	3.5-4.0	180	43
				20	1.50	180	78	52	2.5-3.0	180	73				
				21	1.0	180	76	53	2.5	180	59				
			($\bar{X}$=90) 2/				($\bar{X}$=76±4) 2/				($\bar{X}$=62±13) 2/				($\bar{X}$=44±3) 2/

1/ Range of adhesive thickness.

2/ Mean Value ($\bar{X}$) and estimated standard deviation.

Table 2.2.4 Polyester Adhesive Bond Strength Results Following ASTM C-481, Cycle A, Aging

GROUP B (1.0-2.0 mm)[1/]				GROUP C (2.0-3.0 mm)[1/]				GROUP D (3.0-5.0 mm)[1/]			
SPECIMEN NUMBER	ADHESIVE THICKNESS	TEST TEMP	MAX LOAD	SPECIMEN NUMBER	ADHESIVE THICKNESS	TEST TEMP	MAX LOAD	SPECIMEN NUMBER	ADHESIVE THICKNESS	TEST TEMP	MAX LOAD
	mm	°F	lbs		mm	°F	lbs		mm	°F	lbs
102	1.5-1.75	73	247	101	2.0	73	181	204	3.5	73	158
103	1.5	105	186	104	2.0	105	148	129	3.0	105	104
				105	2.0-2.5	105	155				
110	1.5-2.0	120	132	106	2.0-3.0	120	126				
				107	2.0	120	134				
111	1.5-2.0	150	96	108	2.0-2.5	150	84				
				118	1.75-2.5	150	78				
112	1.75-2.0	180	62	113	2.0-2.5	180	78				
				117	2.0-2.5	180	56				

1/ Range of adhesive thickness

Table 2.2.5 Comparison of Polyester Adhesive Bond Strength With and Without Laboratory Aging[1/]

GROUP B (1.0-2.0 mm)[2/]			GROUP C (2.0-3.0 mm)[2/]			GROUP D (3.0-5.0 mm)[2/]		
TEST TEMP	MAX LOAD W/O AGING	MAX LOAD W. AGING	TEST TEMP	MAX LOAD W/O AGING	MAX LOAD W. AGING	TEST TEMP	MAX LOAD W/O AGING	MAX LOAD W. AGING
°F	lbs	lbs	°F	lbs	lbs	°F	lbs	lbs
73	263	247	73	203	181	73	163	158
105	162	186	105	134	152	105	104	104
120	156	132	120	118	130			
150	115	96	150	67	81			
180	76	62	180	62	67			

1/ Aged by ASTM C481 method

2/ Range of adhesive thickness

Table 2.2.6A Effect of Loading Rate on Polyester Adhesive Bond Strength

GROUP A (<1 mm)[1/]				
SPECIMEN NUMBER	ADHESIVE THICKNESS	TEST TEMP	TIME TO FAILURE	MAX LOAD
	mm	°F	min	lbs
159	0.75	120	0.4	220
160	0.25-0.75	120	0.4	242
188	0.50	120	0.4	230
				($\bar{x}$ = 231)[2/]
150	0.5-0.75	120	3.6	192
151	0.5-1.0	120	3.6	176
				($\bar{x}$ = 184)[2/]
153	0.3-1.5	120	32.4	120
154	0.5-0.75	120	27.6	137
				($\bar{x}$ = 129)[2/]
178	0.75-1.0	180	0.4	92
190	0.5	180	0.4	87
				($\bar{x}$ = 90)[2/]
162	0.75	180	2.6	67
165	0.5-0.75	180	2.8	70
				($\bar{x}$ = 69)[2/]
173	0.75-1.0	180	25.6	53

1/ Range of polyester adhesive thickness

2/ $\bar{x}$ is the mean value

Table 2.2.6B Effect of Loading Rate on Polyester Adhesive Bond Strength

GROUP B (1.0-2.0 mm)[1/]				
SPECIMEN NUMBER	ADHESIVE THICKNESS	TEST TEMP	TIME TO FAILURE	MAX LOAD
	mm	°F	min	lbs
See Table 2.2.3		120	0.4	($\bar{x}$ = 150)[2/]
114 116	1.5-2.5 1.5-2.0	120 120	3.1 3.0	84 94 ($\bar{x}$ = 89)[2/]
121 128 132	1.5 1.5 1.5-2.0	120 120 120	25.8 24.8 26.4	78 67 78 ($\bar{x}$ = 74)[2/]
See Table 2.2.3		150	0.4	($\bar{x}$ = 115)[2/]
152 155	1.0-1.5 1.0-1.5	150 150	3.2 3.0	86 66 ($\bar{x}$ = 76)[2/]
156 158 163	1.0-2.0 0.75-1.25 0.5-1.5	150 150 150	29.0 29.4 24.4	56 70 50 ($\bar{x}$ = 59)[2/]
See Table 2.2.3		180	0.4	($\bar{x}$ = 76)[2/]
164 167 168	1.25 1.0-1.75 1.0-1.25	180 180 180	2.2 2.2 2.4	55 60 49 ($\bar{x}$ = 55)[2/]
169 171	1.25 0.5-2.0	180 180	21.4 19.6	45 46 ($\bar{x}$ = 46)[2/]

1/ Range of polyester adhesive thickness

2/ $\bar{x}$ is the mean value

Table 2.2.6C Effect of Loading Rate on Polyester Adhesive Bond Strength

GROUP C (2.0-3.0 mm)[1/]				
SPECIMEN NUMBER	ADHESIVE THICKNESS	TEST TEMP	TIME TO FAILURE	MAX LOAD
	mm	°F	min	lbs
See Table 2.2.3		105	0.4	($\bar{x}$ = 134)[2/]
120 122	2.0 2.0	105 105	1.9 2.0	95 85 ($\bar{x}$ = 90)[2/]
123 124	2.0 2.5	105 105	19.3 14.8	105 52
See Table 2.2.3		120	0.4	($\bar{x}$ = 118)[2/]
130 131 134 133	2.5-3.0 2.0 2.5-3.0 2.5-3.5	120 120 120 120	3.4 3.2 3.4 4.0	62 56 70 62 ($\bar{x}$ = 63)[2/]
125 126 127	2.0 2.0 2.5-3.0	120 120 120	39.8 27.2 27.6	81 70 36 ($\bar{x}$ = 62)[2/]

1/. Range of polyester adhesive thickness

2/ $\bar{x}$ is the mean value

Table 2.2.7 Effect of Sustained Load on Time to Failure for Polyester Adhesive Bond[1/]

Sustained Load	Apparatus	Time to Failure	Mean Value of Time to Failure
lbs		hrs	hrs
100	Testing Machine	0.0060, 0.0045, 0.0040, 0.0049 0.0072, 0.0080, 0.0062 0.0055, 0.0058 0.0057	0.0058
60	Testing Machine	0.030, 0.050, 0.060, 0.062, 0.055, 0.045	0.050
50	Testing Machine	0.20, 0.31	0.25
40	Testing Machine	1.2, 2.0, 1.9, 3.7	2.2
40	Dead Load Apparatus	1.5, 2.5, 1.8, 2.3	2.0
35	Dead Load Apparatus	296, (2 specimens had no failure after 3000 hours)	> 2097
25	Dead Load Apparatus	728, (2 specimens had no failure after 3500 hours)	>2576

1/ All specimens had adhesive thickness between 1.0 and 2.0 mm and were tested at 150°F.

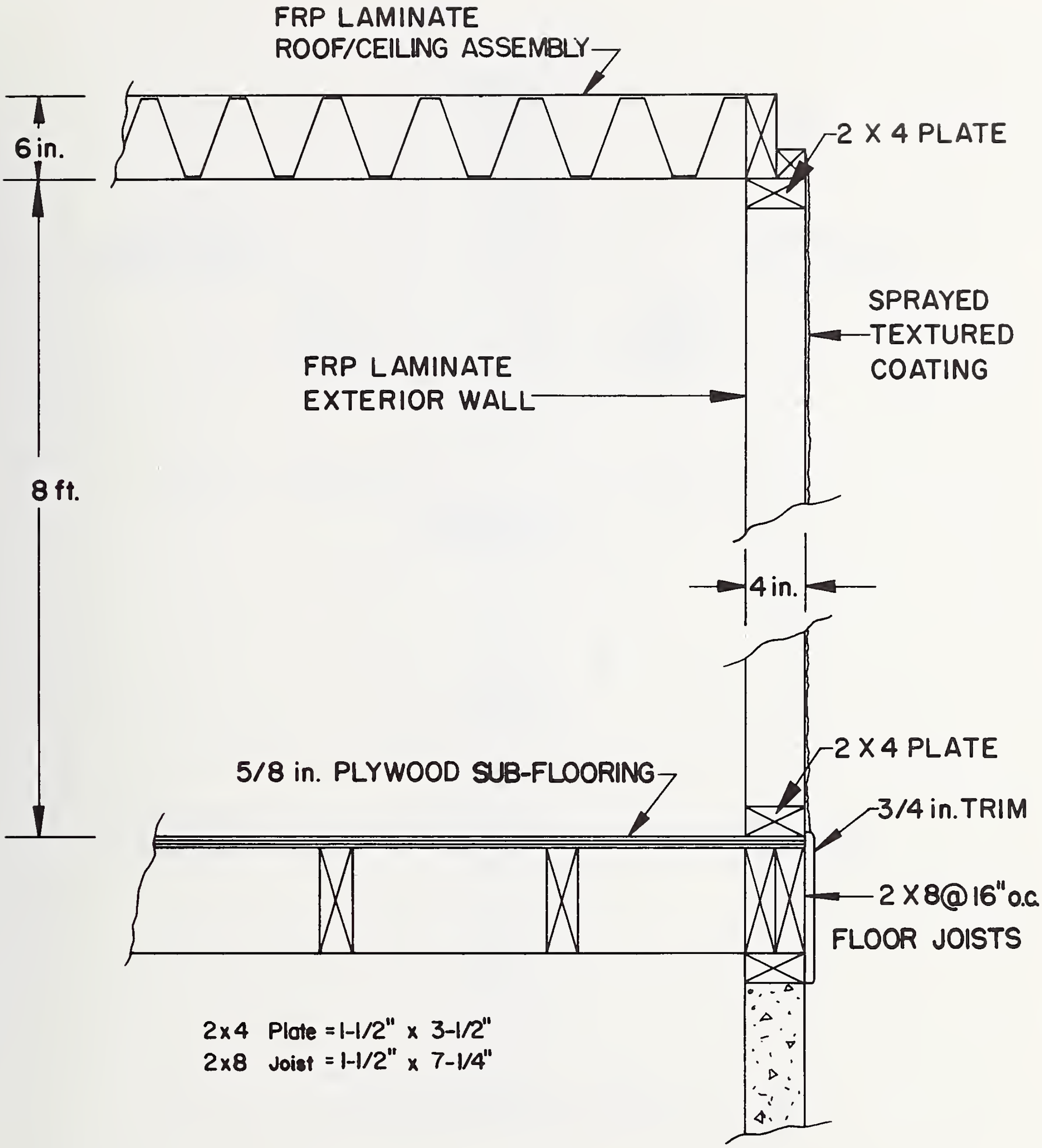

Fig. 1.2.1 Typical section for the FRP laminate housing system.

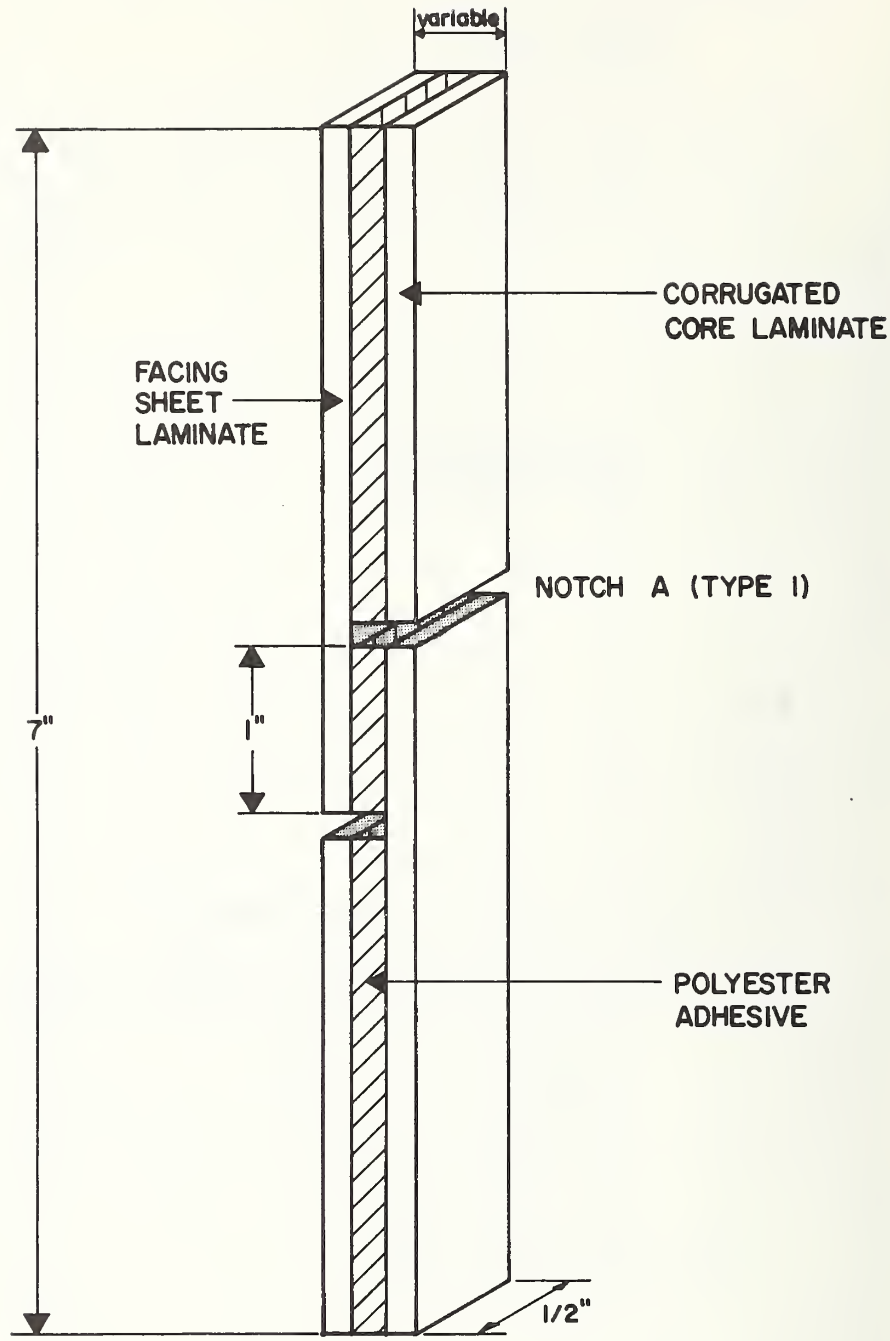

Fig. 2.2.1 Adhesive bond specimen with notch type 1.

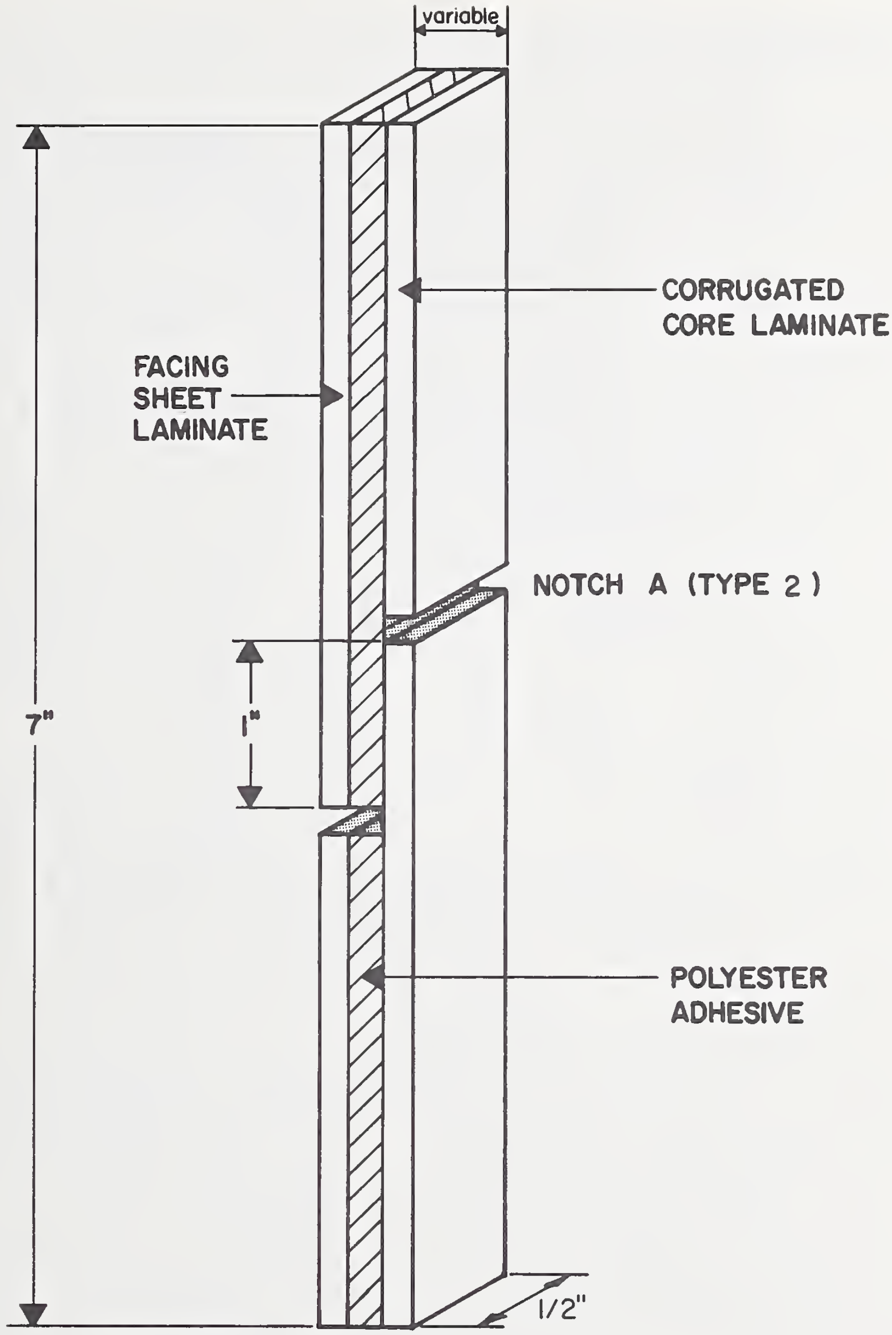

Fig. 2.2.2 Adhesive bond specimen with notch type 2.

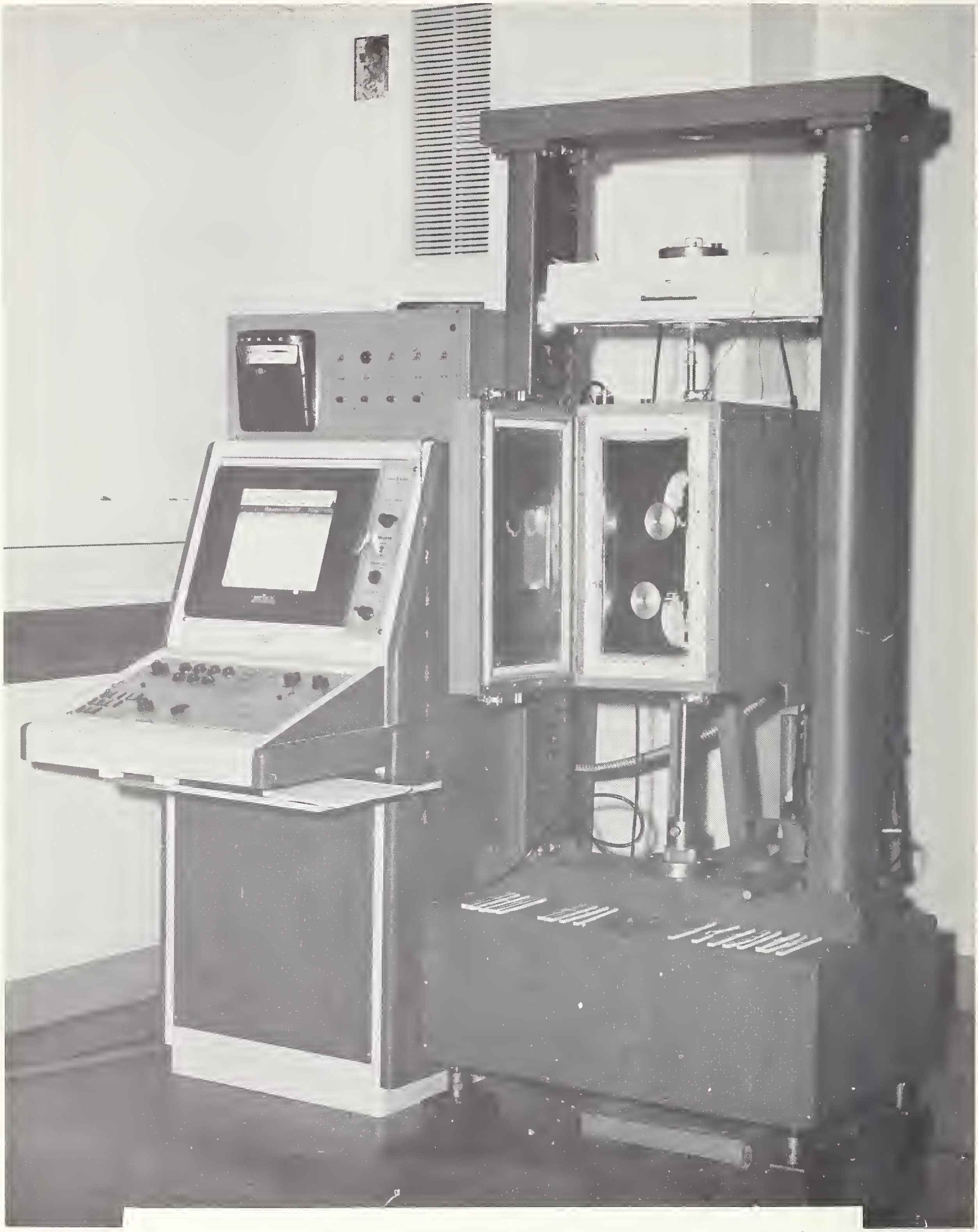

Fig. 2.2.3 Testing machine and temperature chamber.

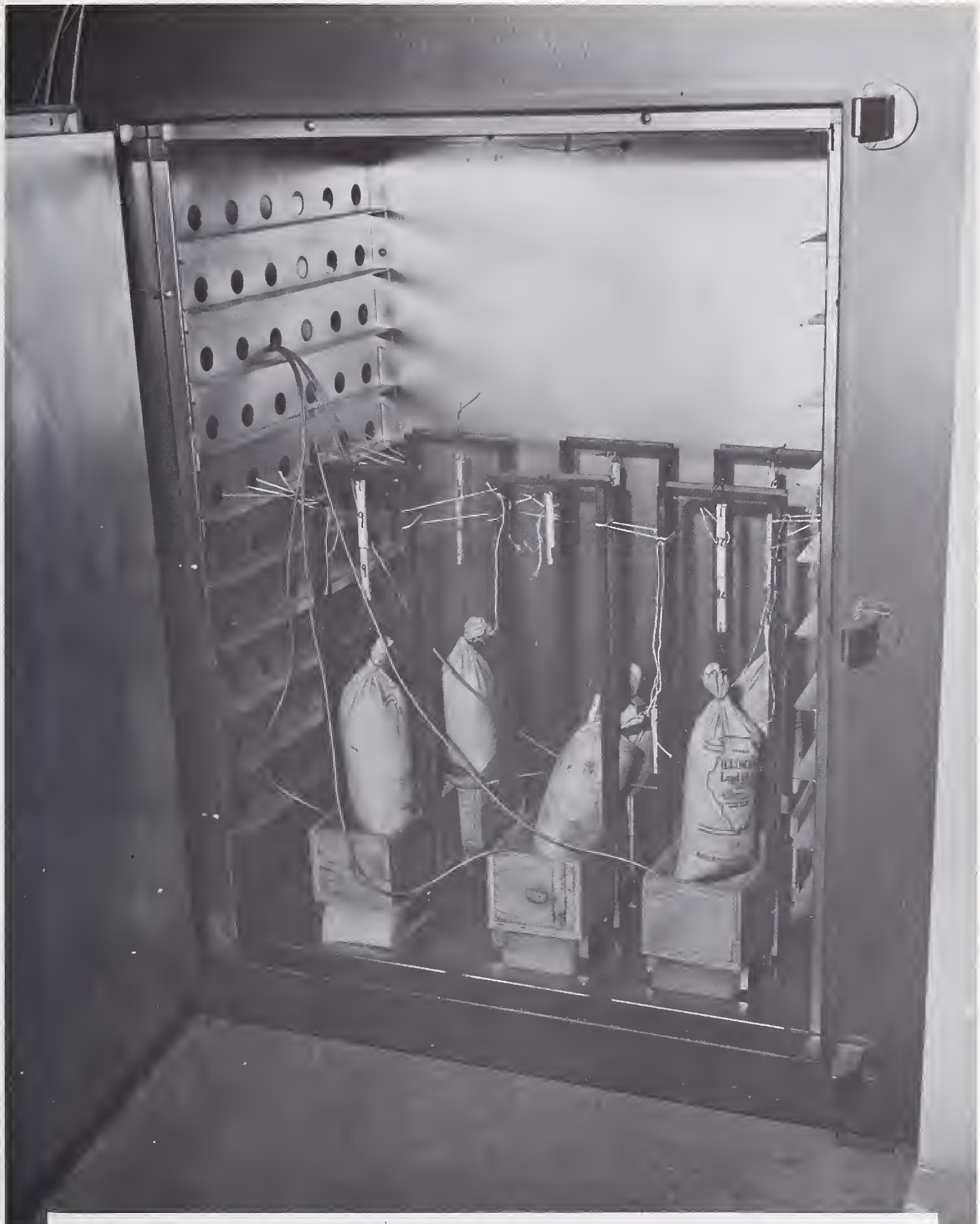

Fig. 2.2.4 Sustained loading apparatus and temperature chamber.

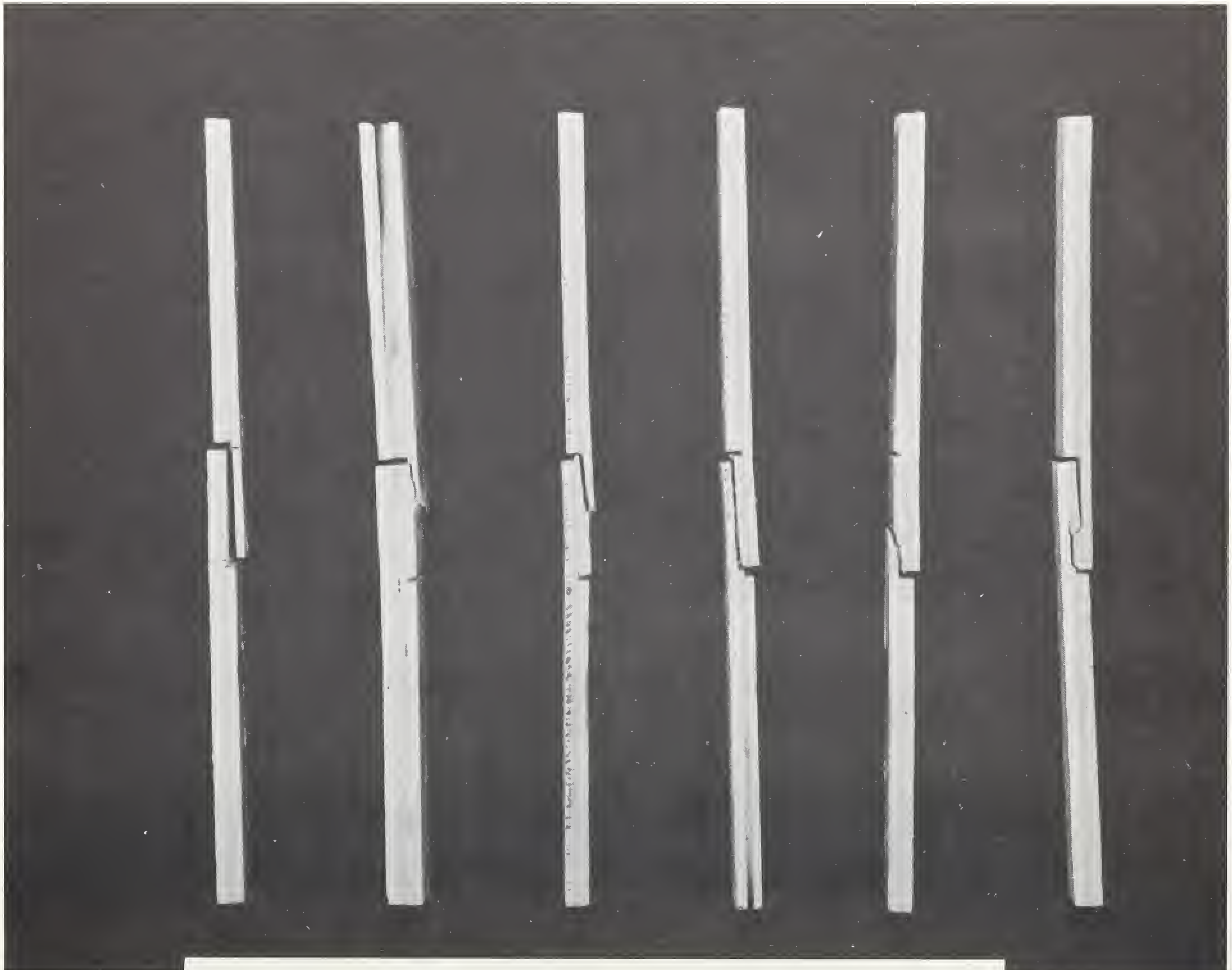

Fig. 2.2.5 Typical failures in specimens with notch type 2.

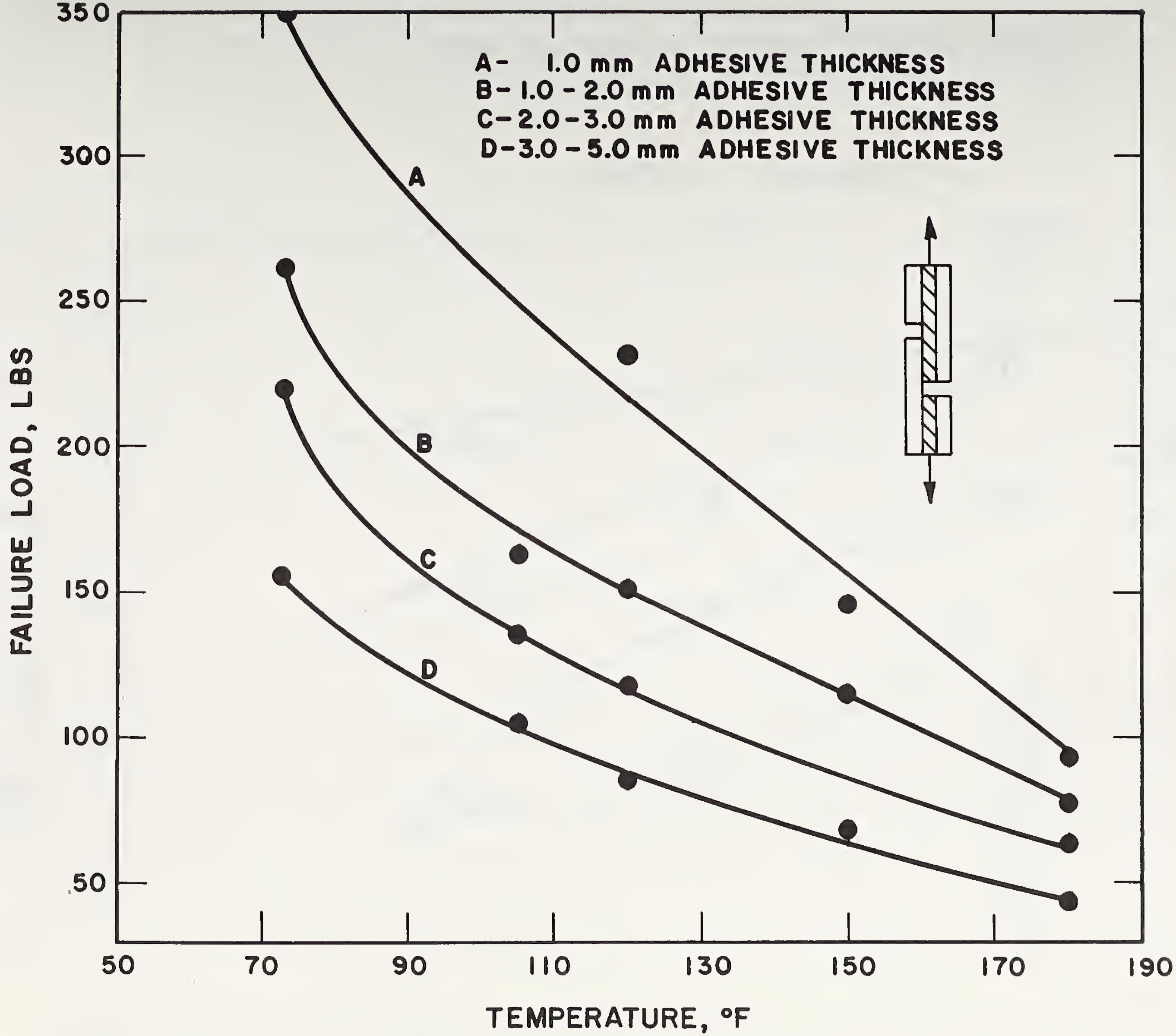

Fig. 2.2.6 Effect of temperature on bond strength.

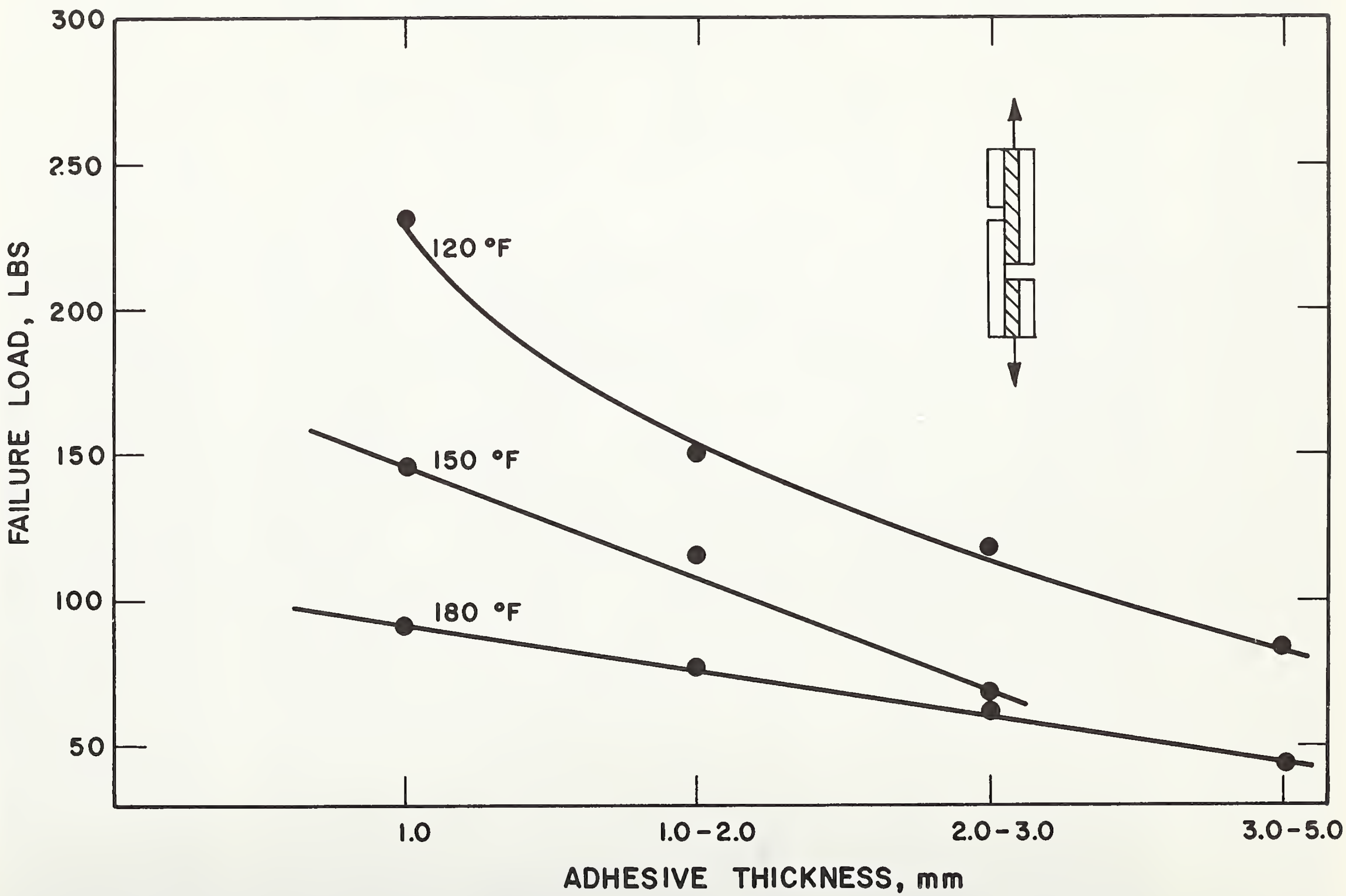

Fig. 2.2.7 Effect of adhesive thickness on bond strength.

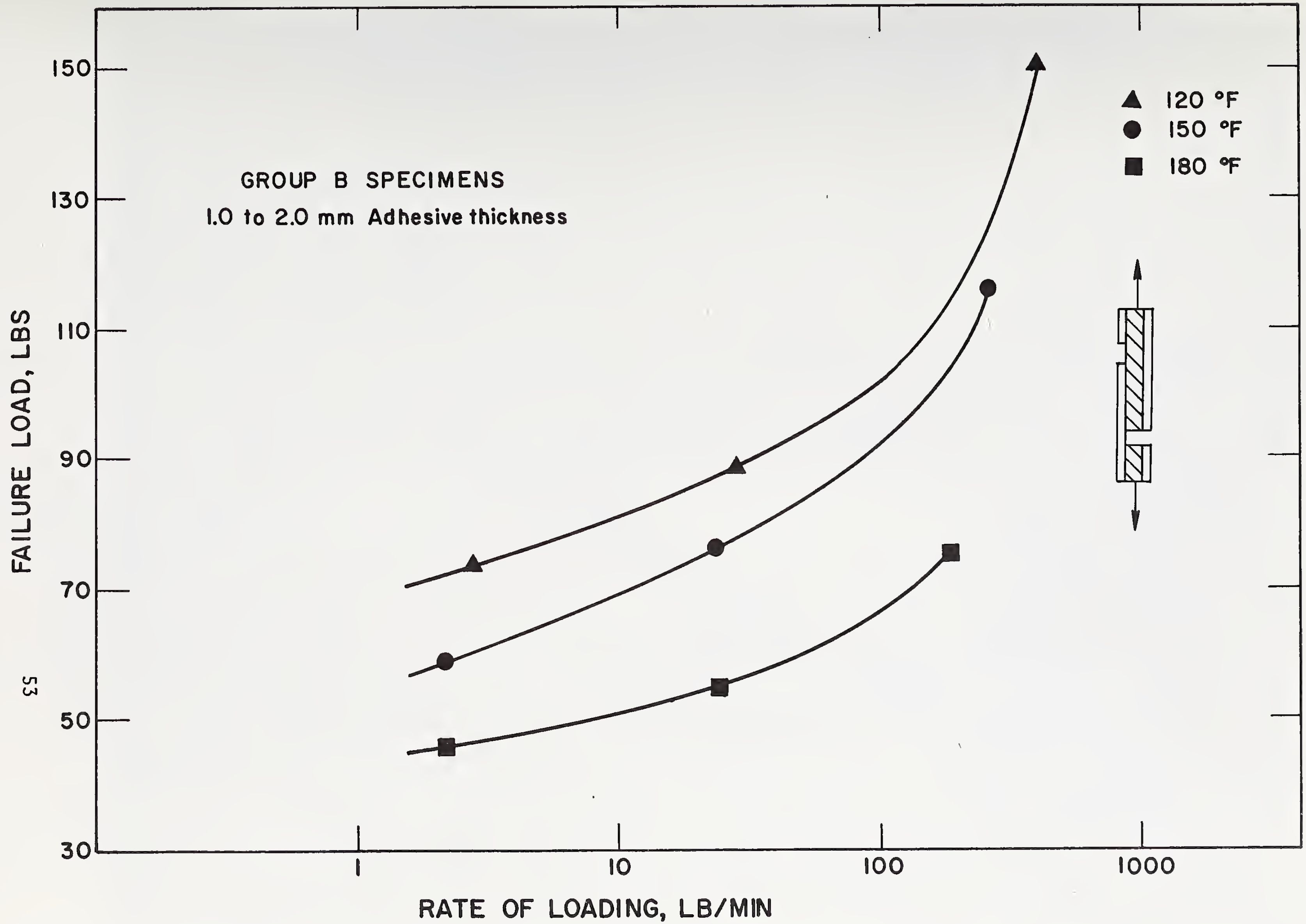

Fig. 2.2.8 Effect of loading rate on bond strength.

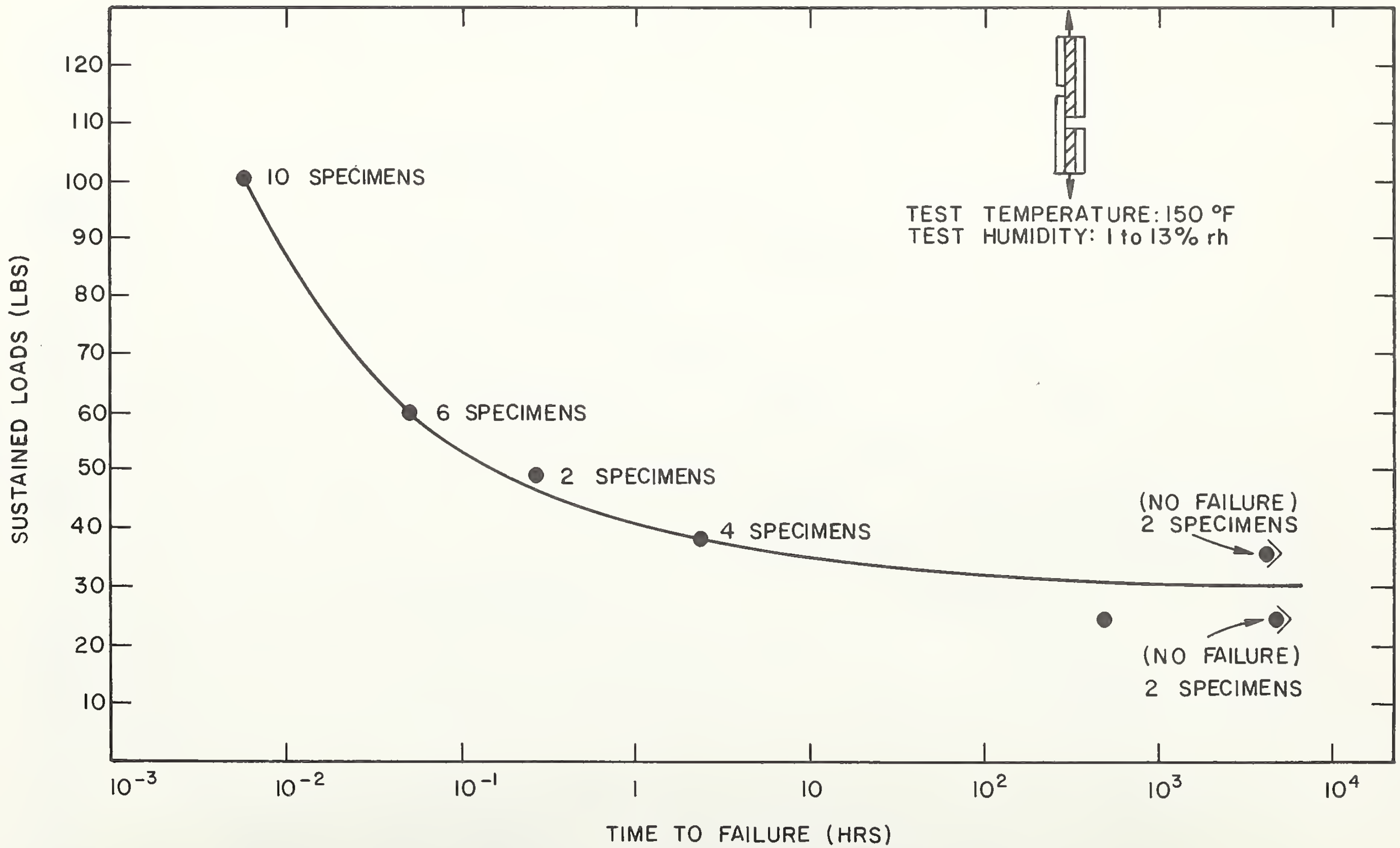

Fig. 2.2.9 Effect of sustained-load magnitude on time-to-failure.

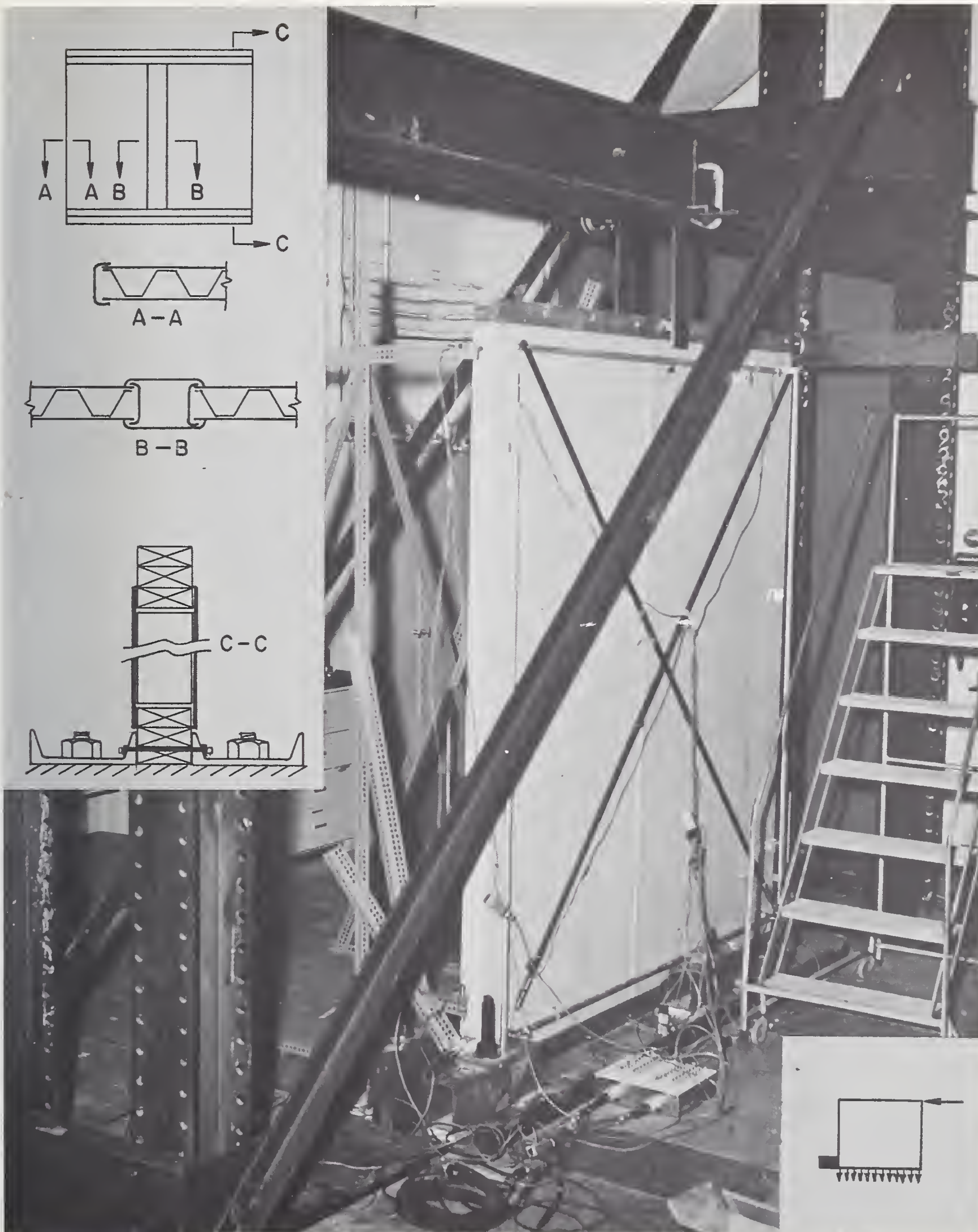

Fig. 2.3.1 Test setup for racking test No. 1

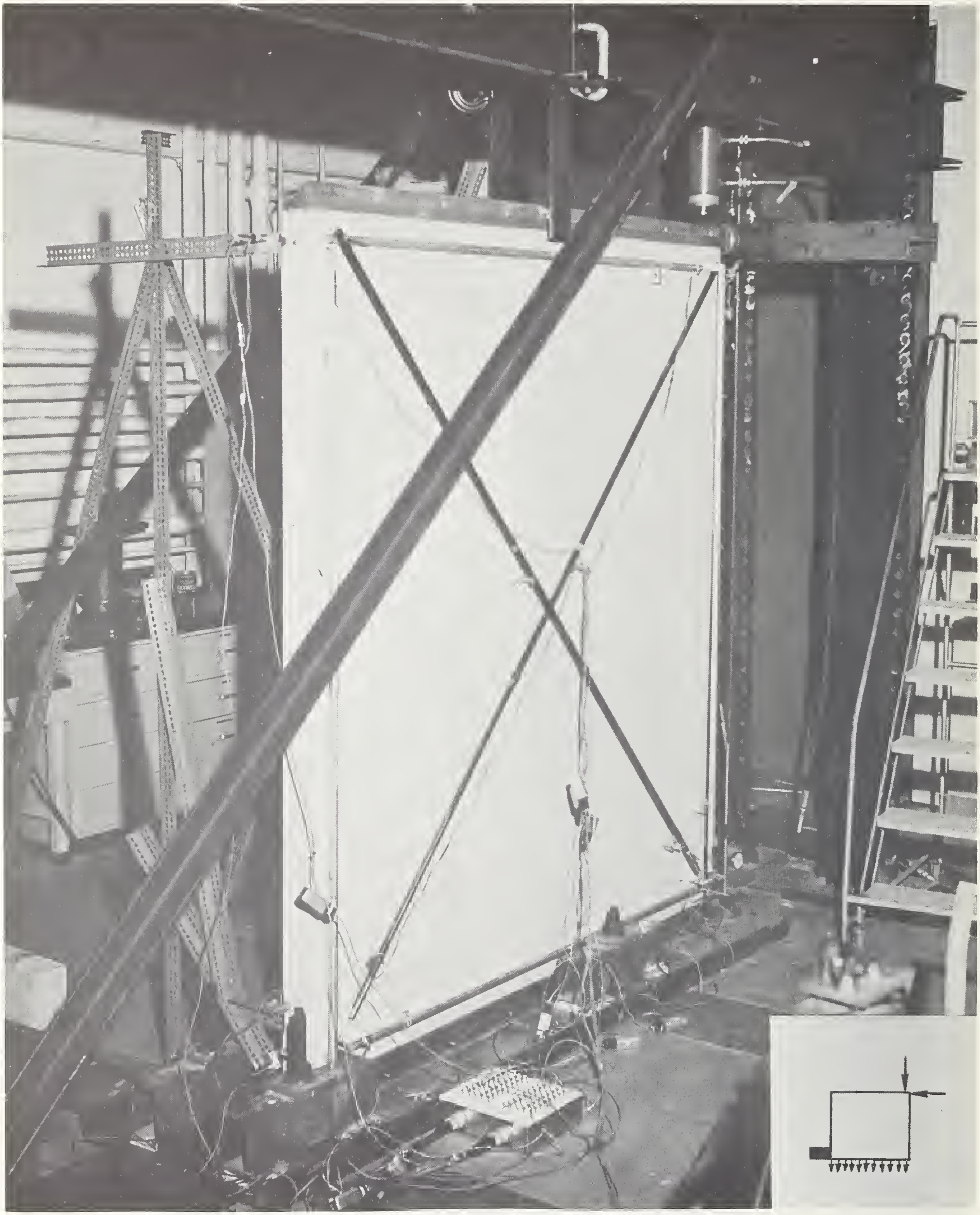

Fig. 2.3.2 Test setup for racking test No. 2.. 56

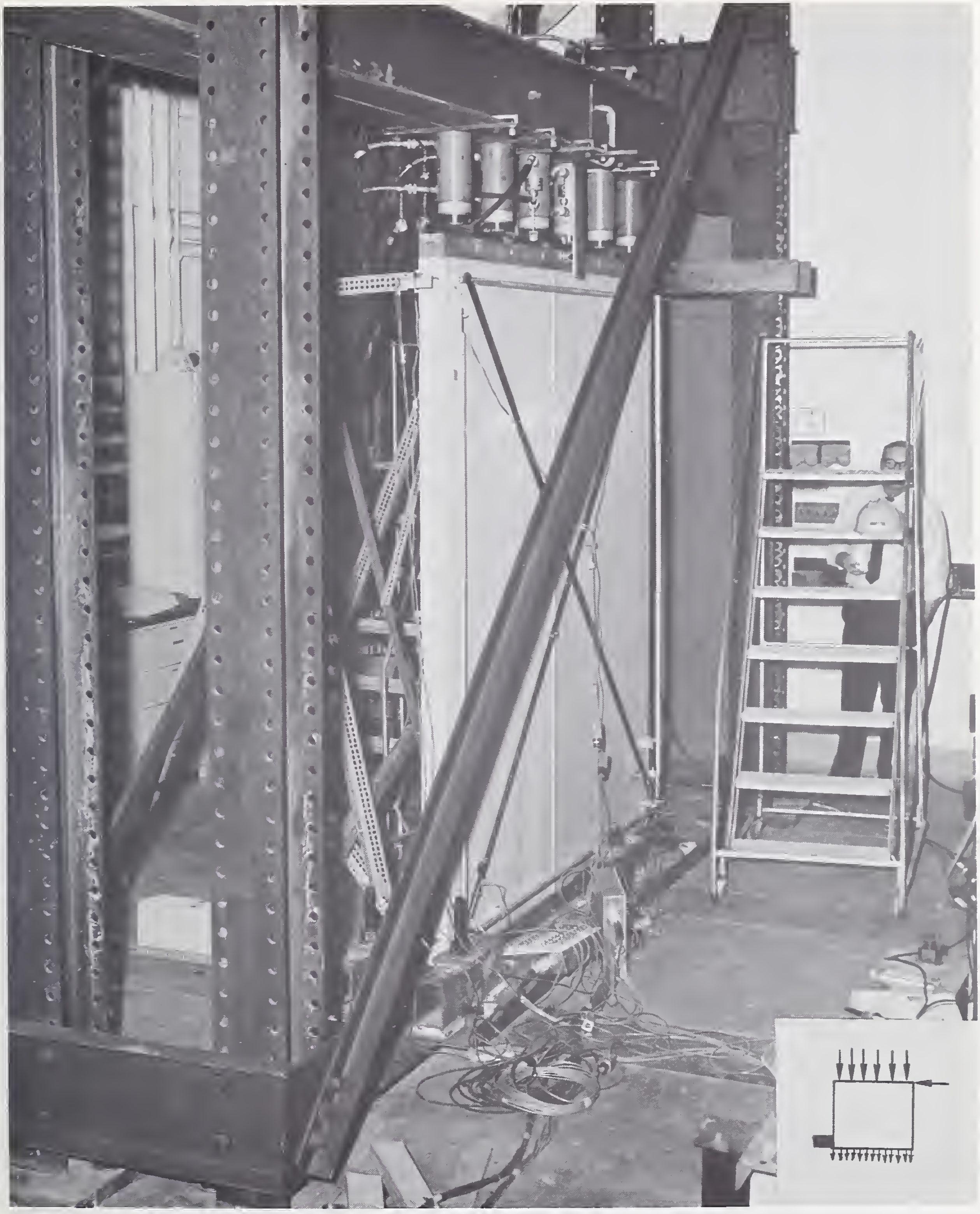

Fig. 2.3.3 Test setup for racking test No. 3.

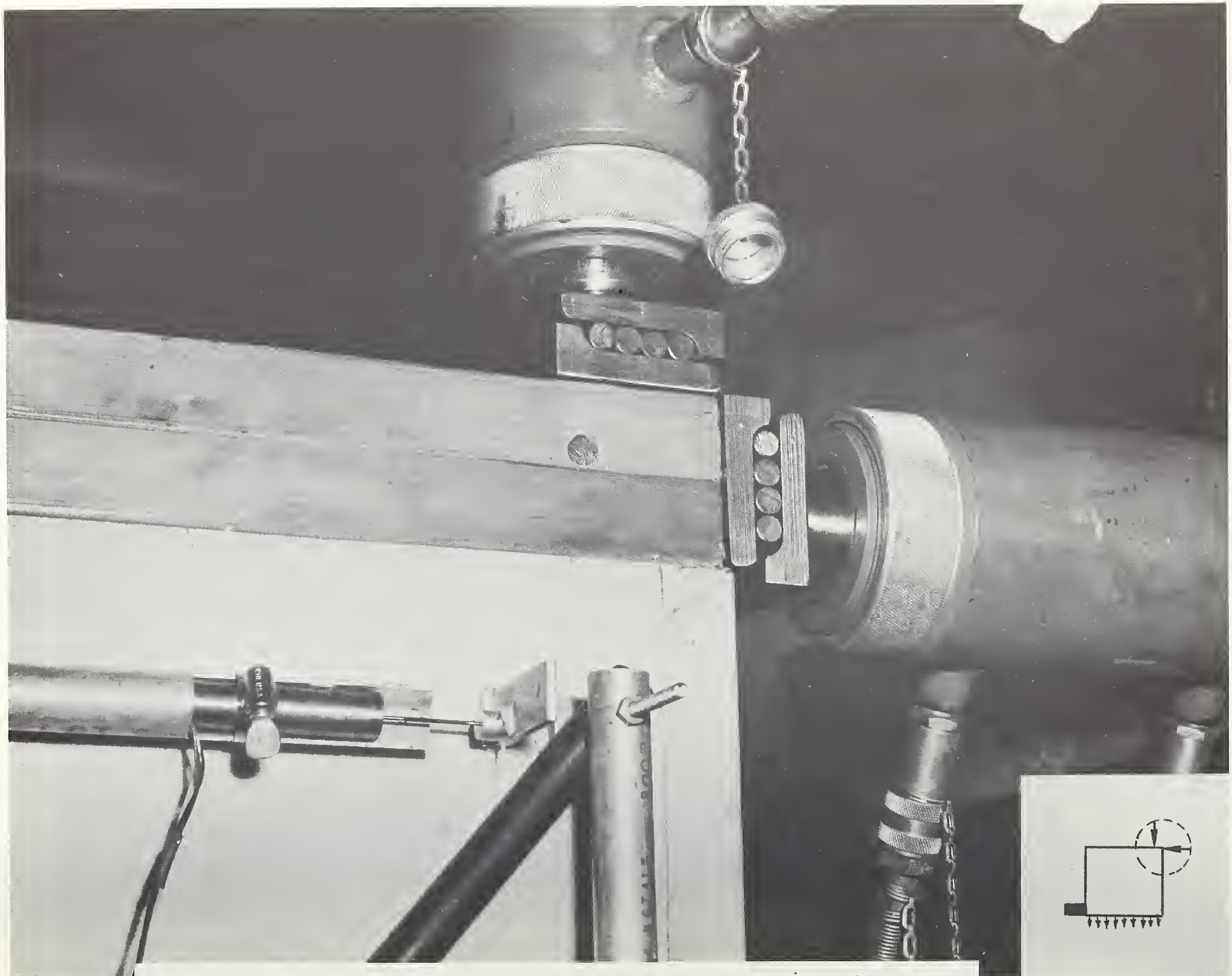

Fig. 2.3.4 Detail of roller bearings and transducers used in racking tests.

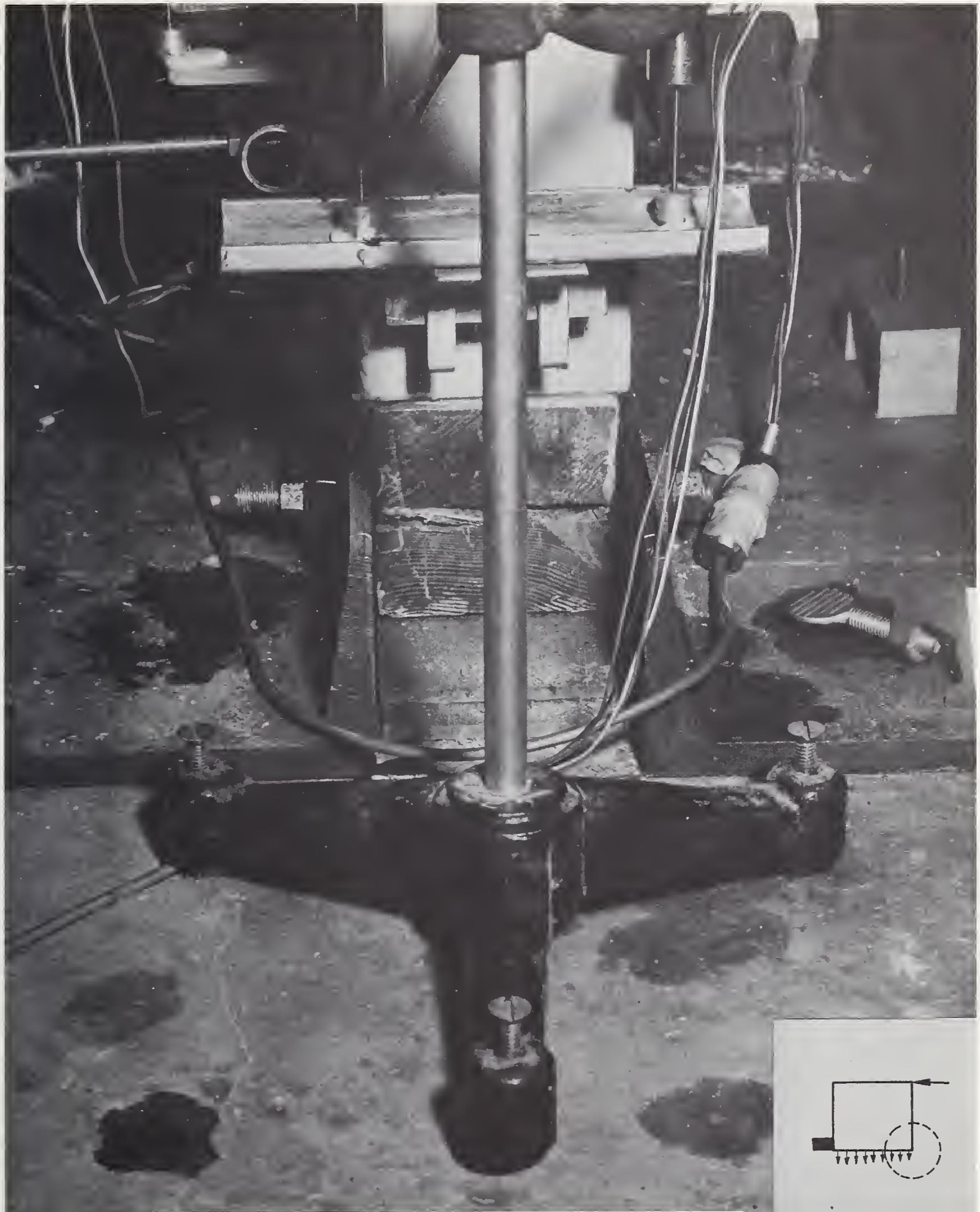

Fig. 2.3.5 Failure in racking test No. 1.

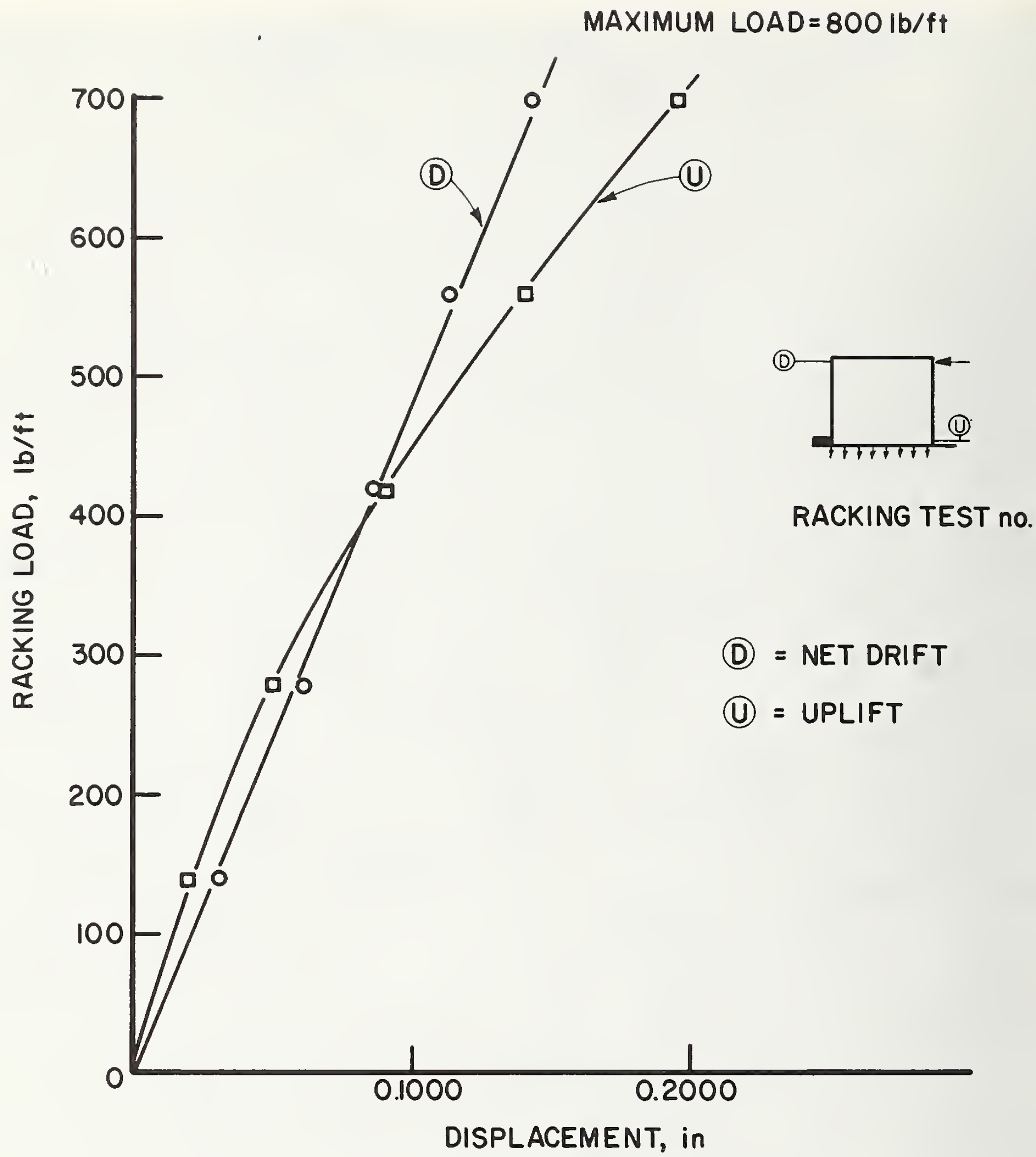

Fig. 2.3.6 Load vs. displacement for racking test No. 1.

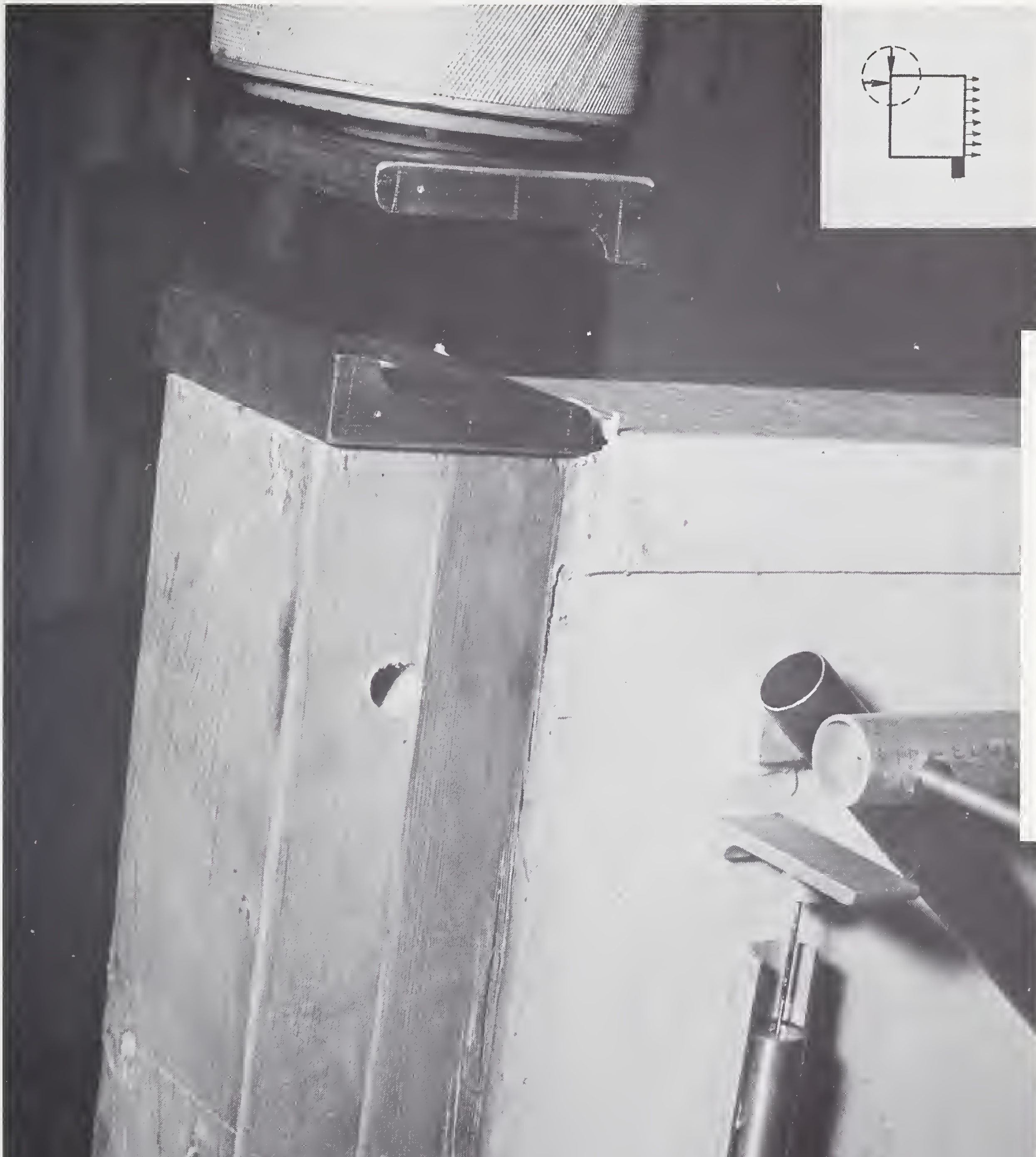

Fig. 2.3.7 Failure in racking test No. 2.

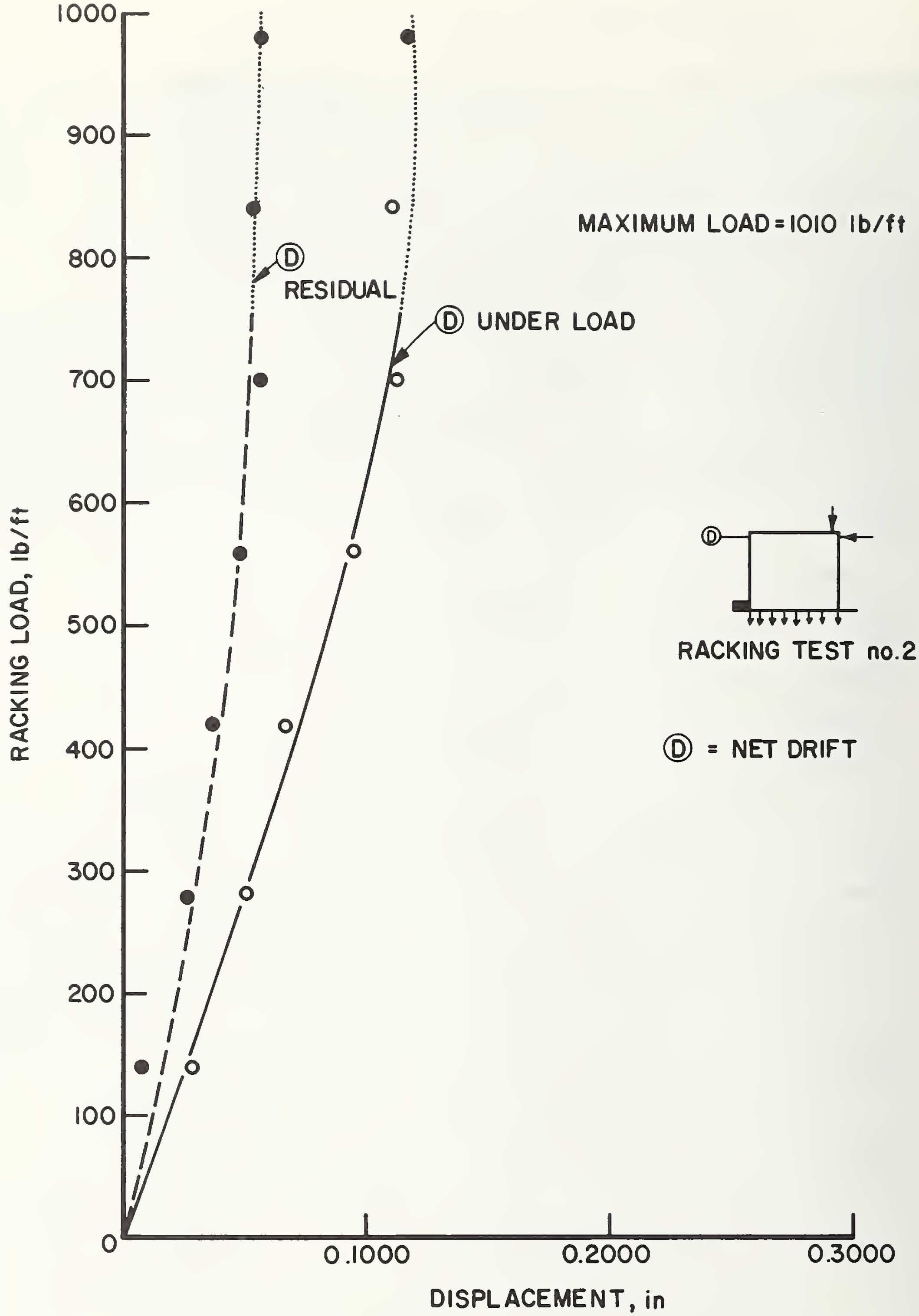

Fig. 2.3.8 Load vs. displacement for racking test No. 2.

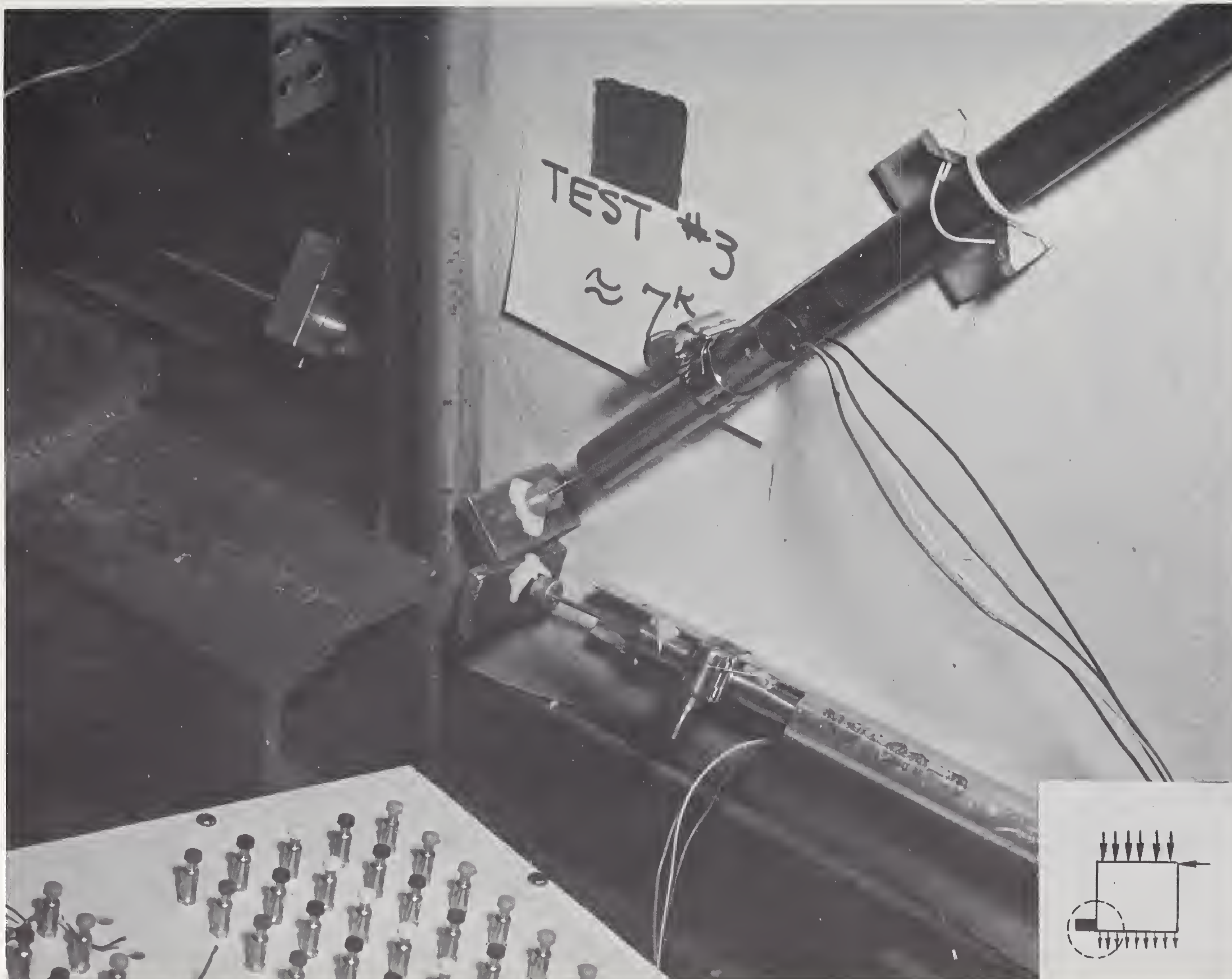

Fig. 2.3.9 Failure in racking test No. 3.

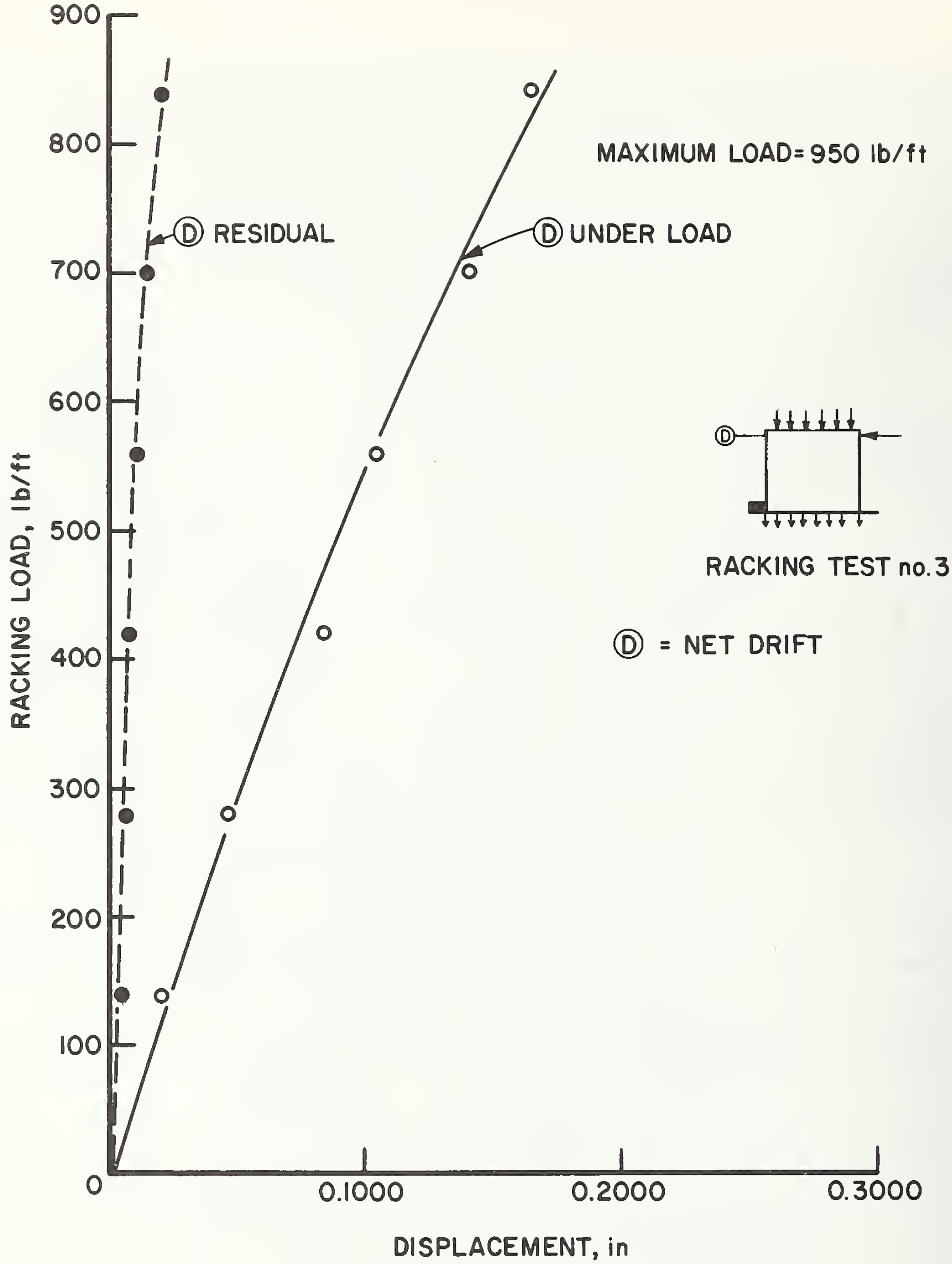

Fig. 2.3.10 Load vs. displacement for racking test No. 3.

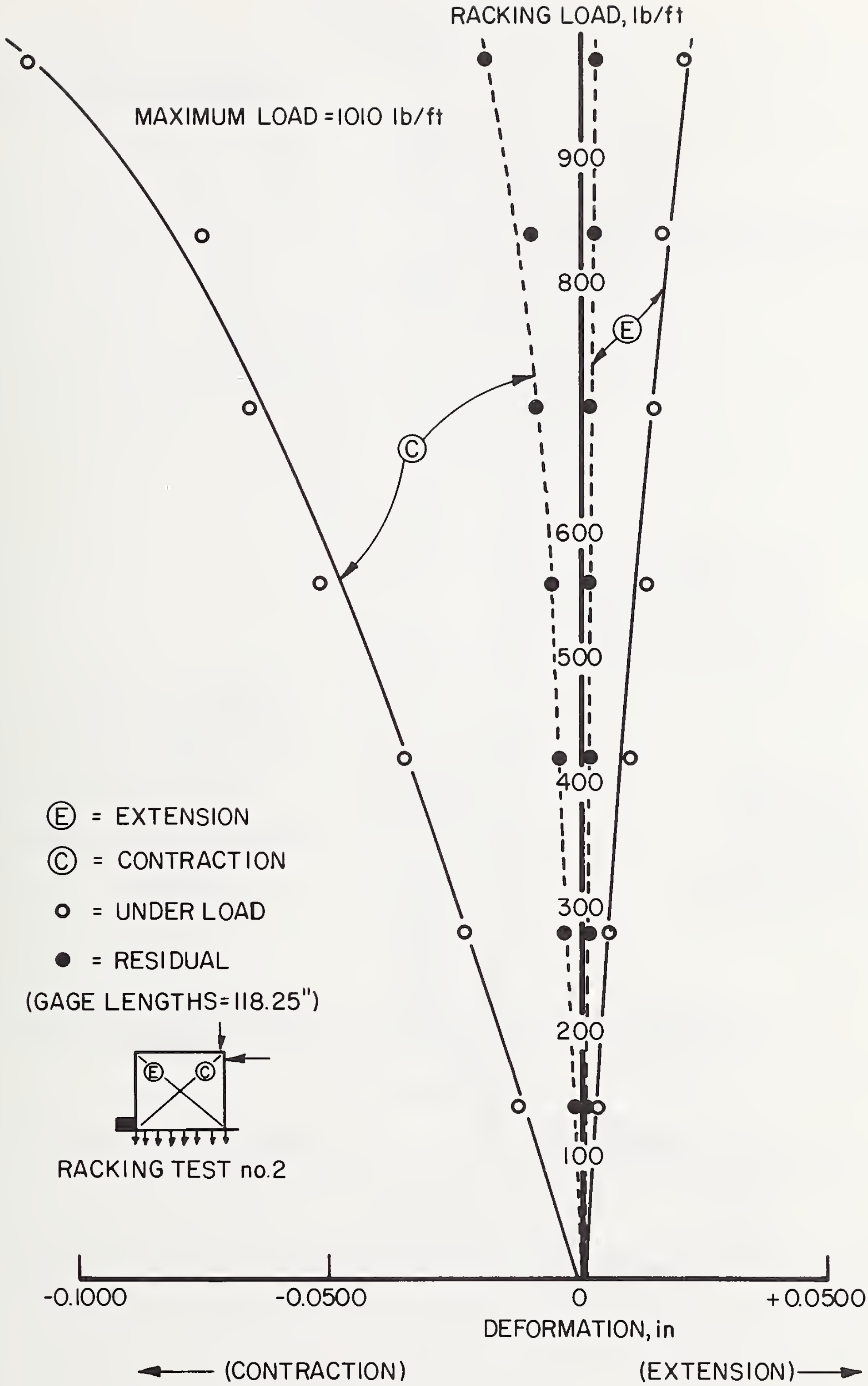

Fig. 2.3.12 Load vs. diagonal deformation for racking test No. 2.

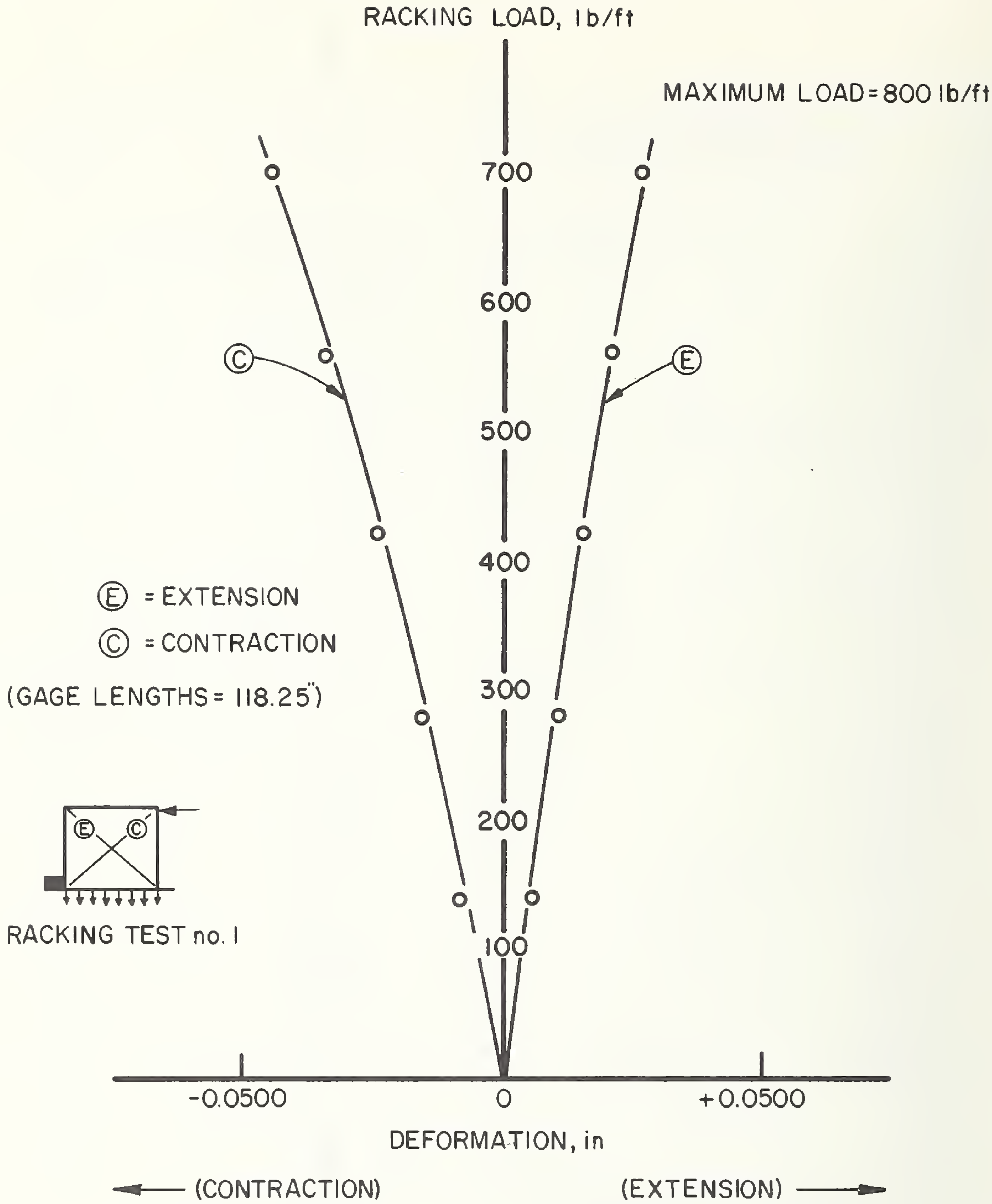

Fig. 2.3.11 Load vs. diagonal deformation for racking test No. 1.

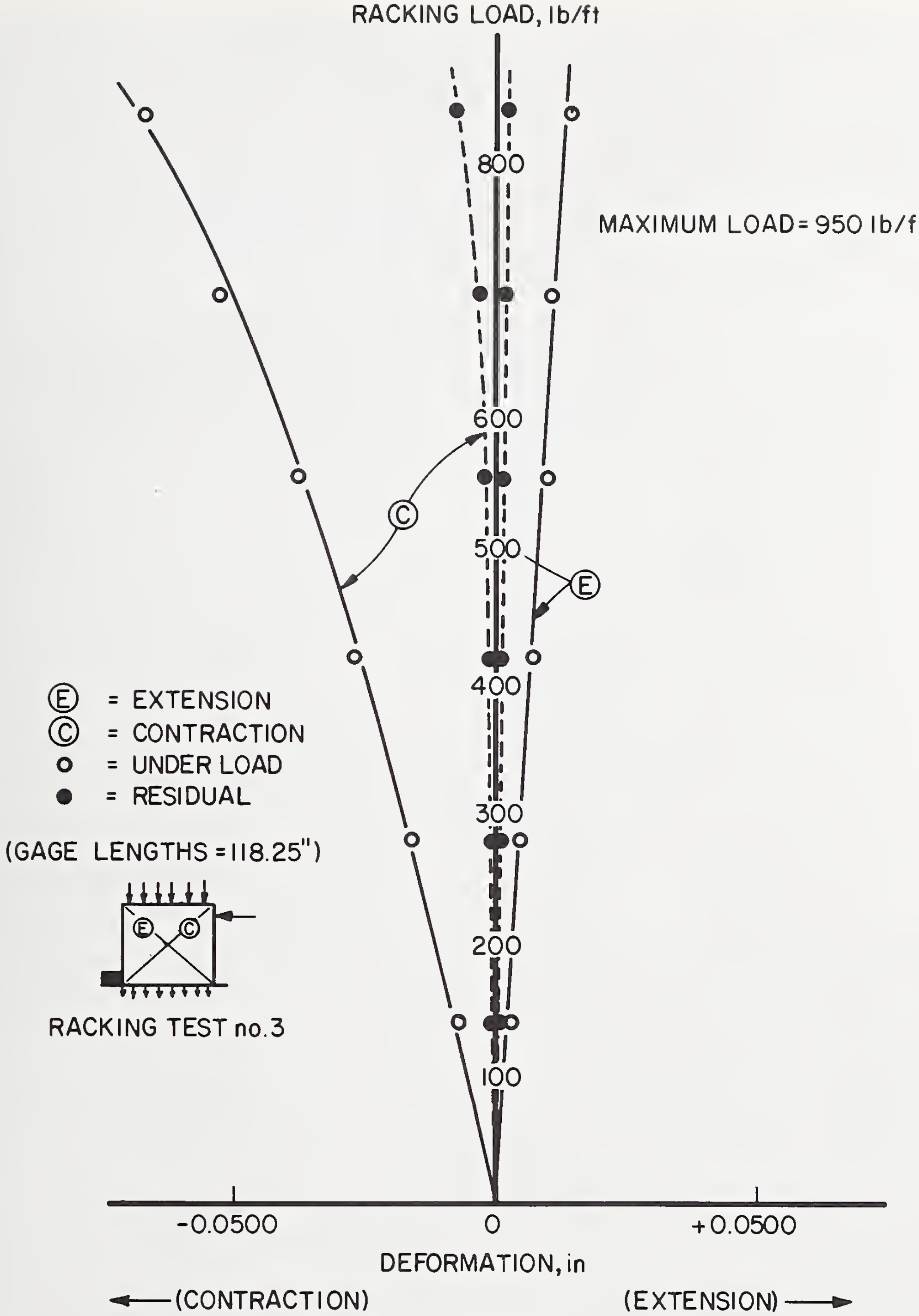

Fig. 2.3.13 Load vs. diagonal deformation for racking test No. 3.

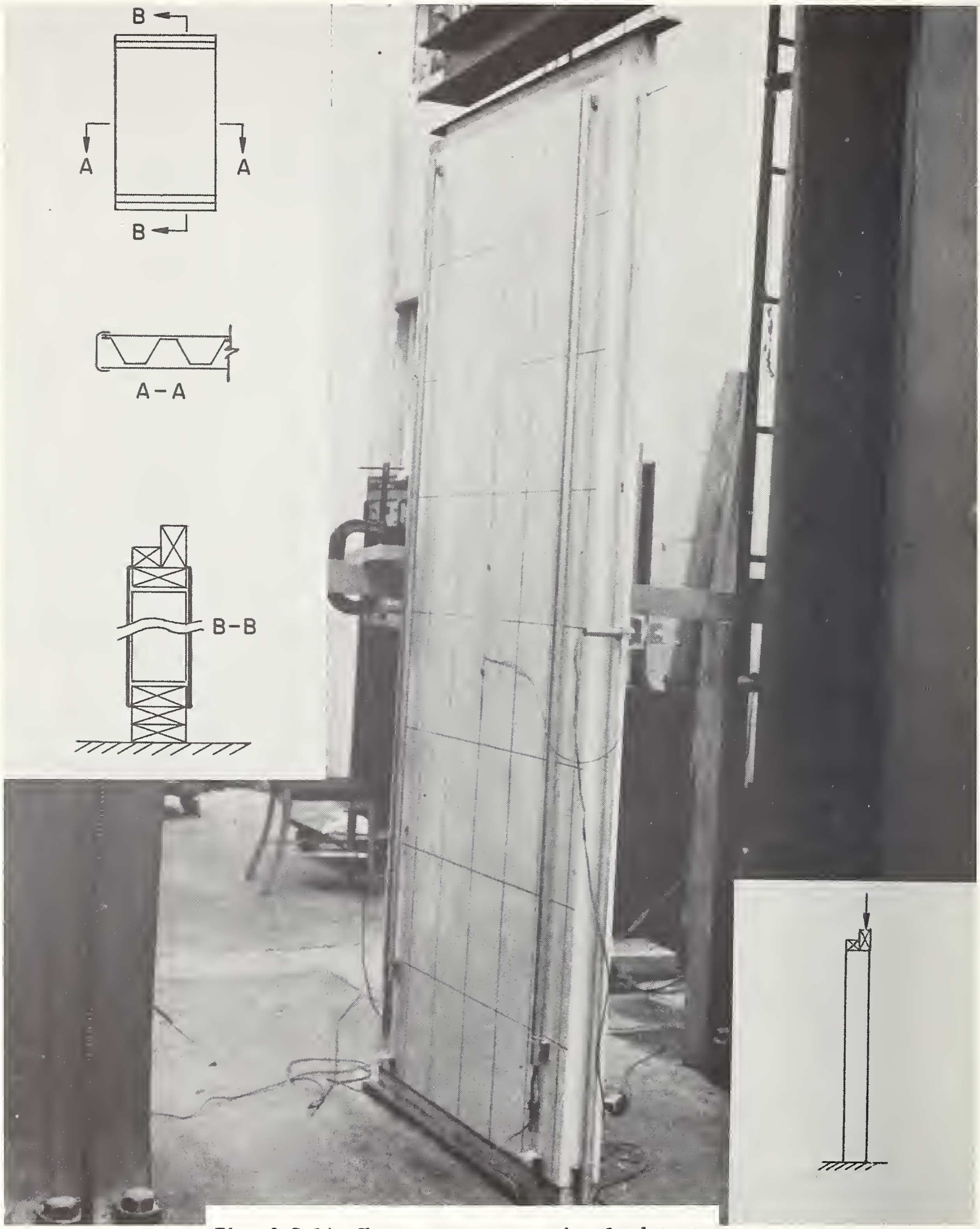

Fig. 2.3.14 Short-term compressive load test.

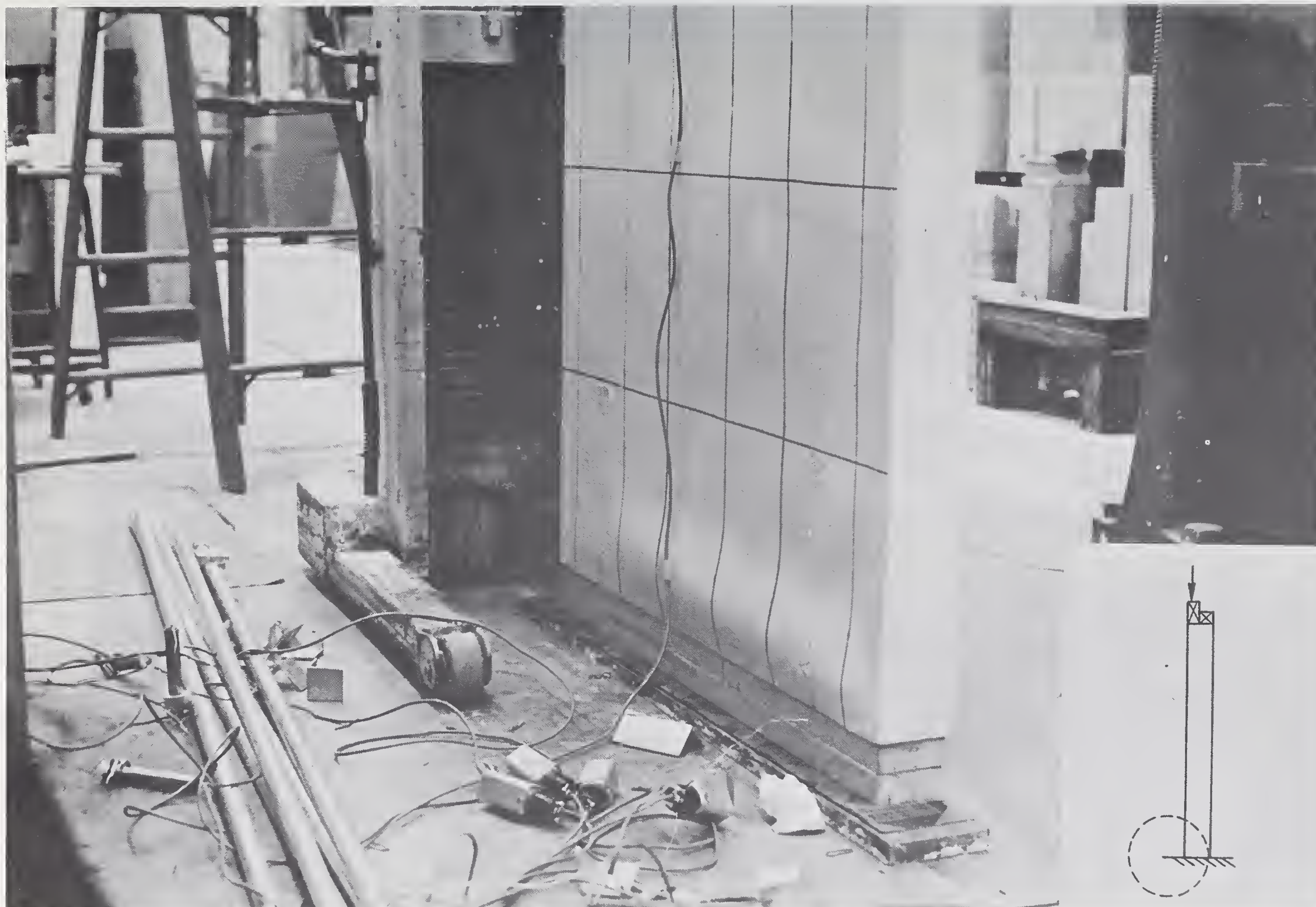

Fig. 2.3.15 Failure in short-term compressive test No. 1.

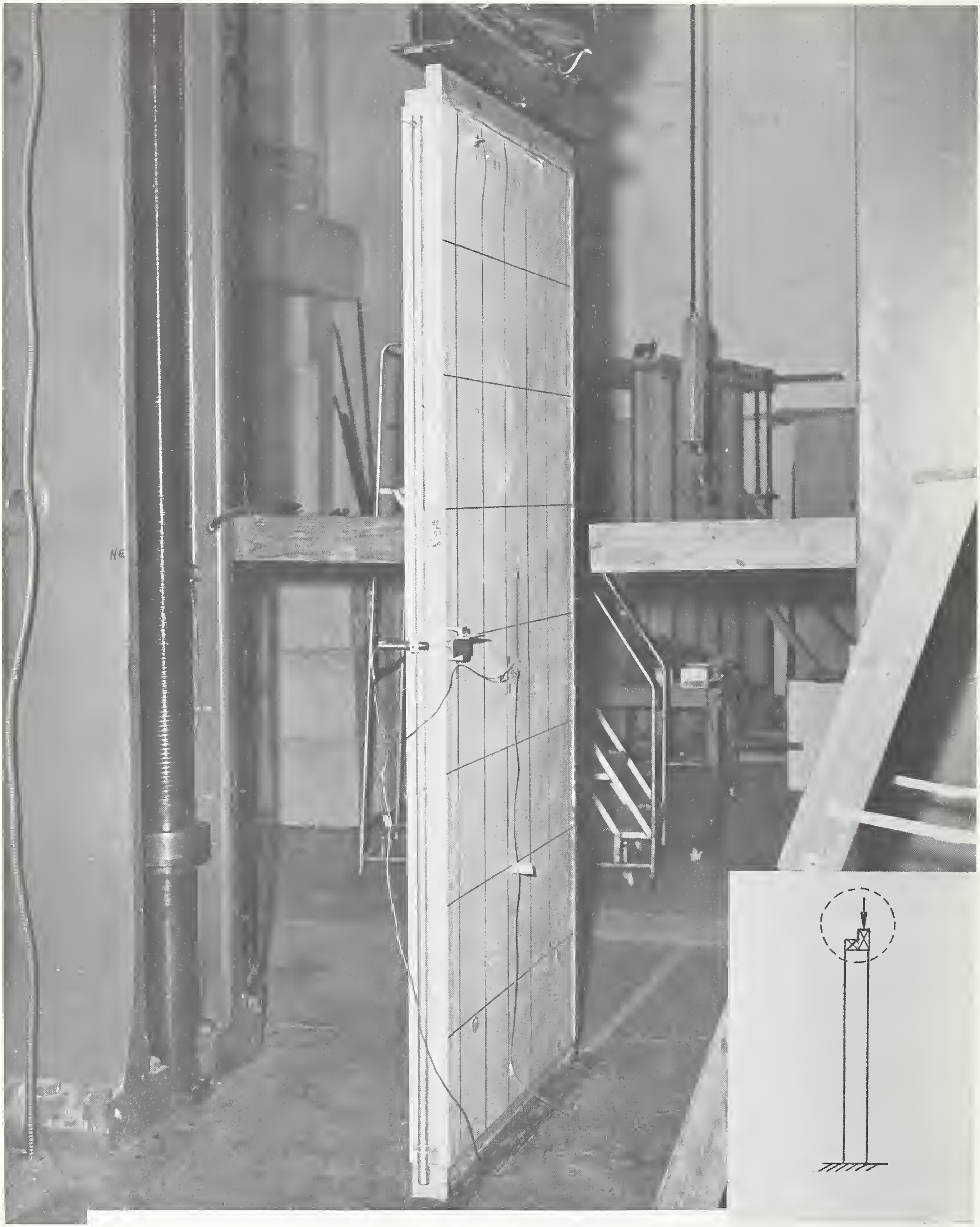

Fig. 2.3.16 Failure in short-term compressive test No. 2.

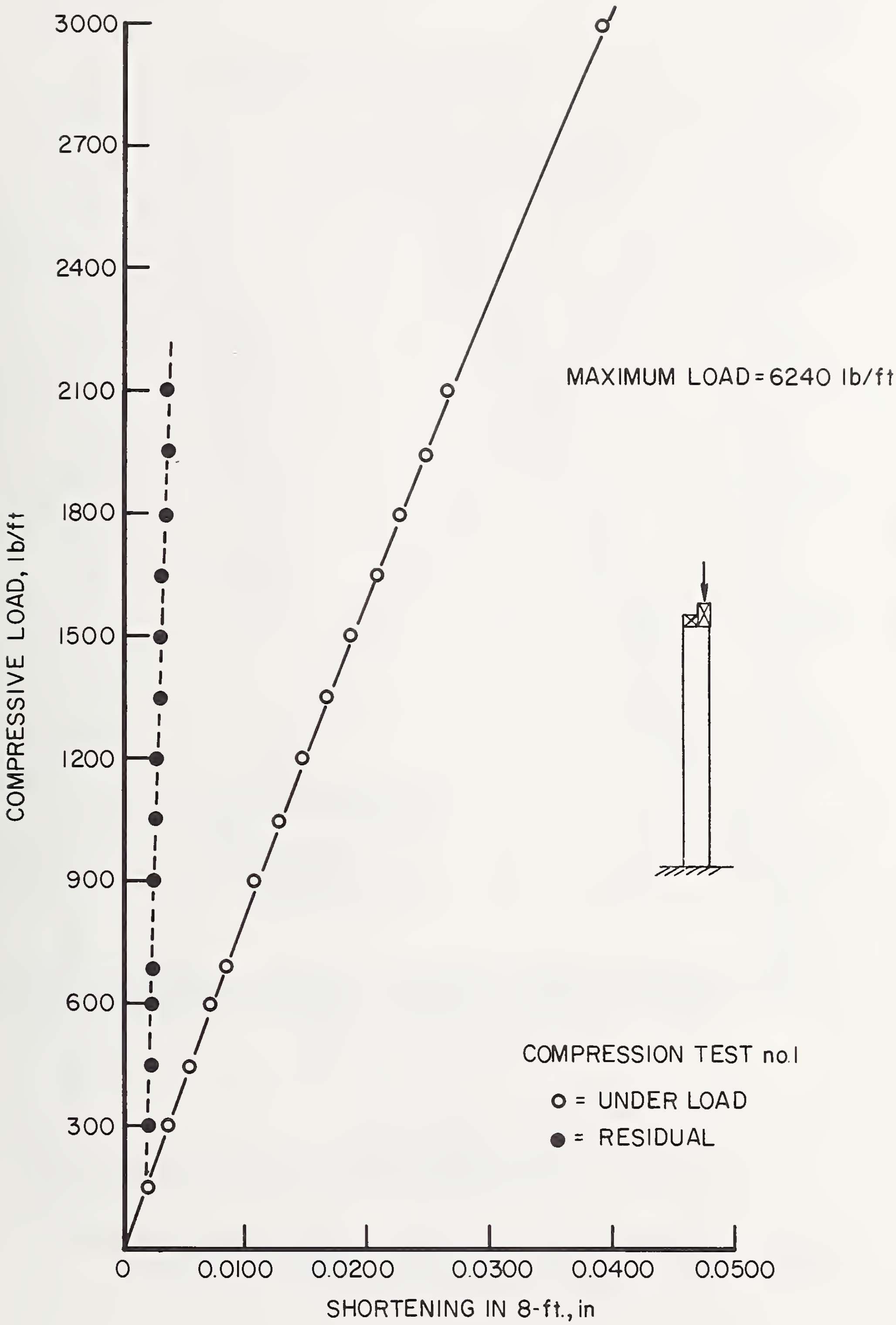

Fig. 2.3.17 Load vs. shortening for compressive test No. 1.

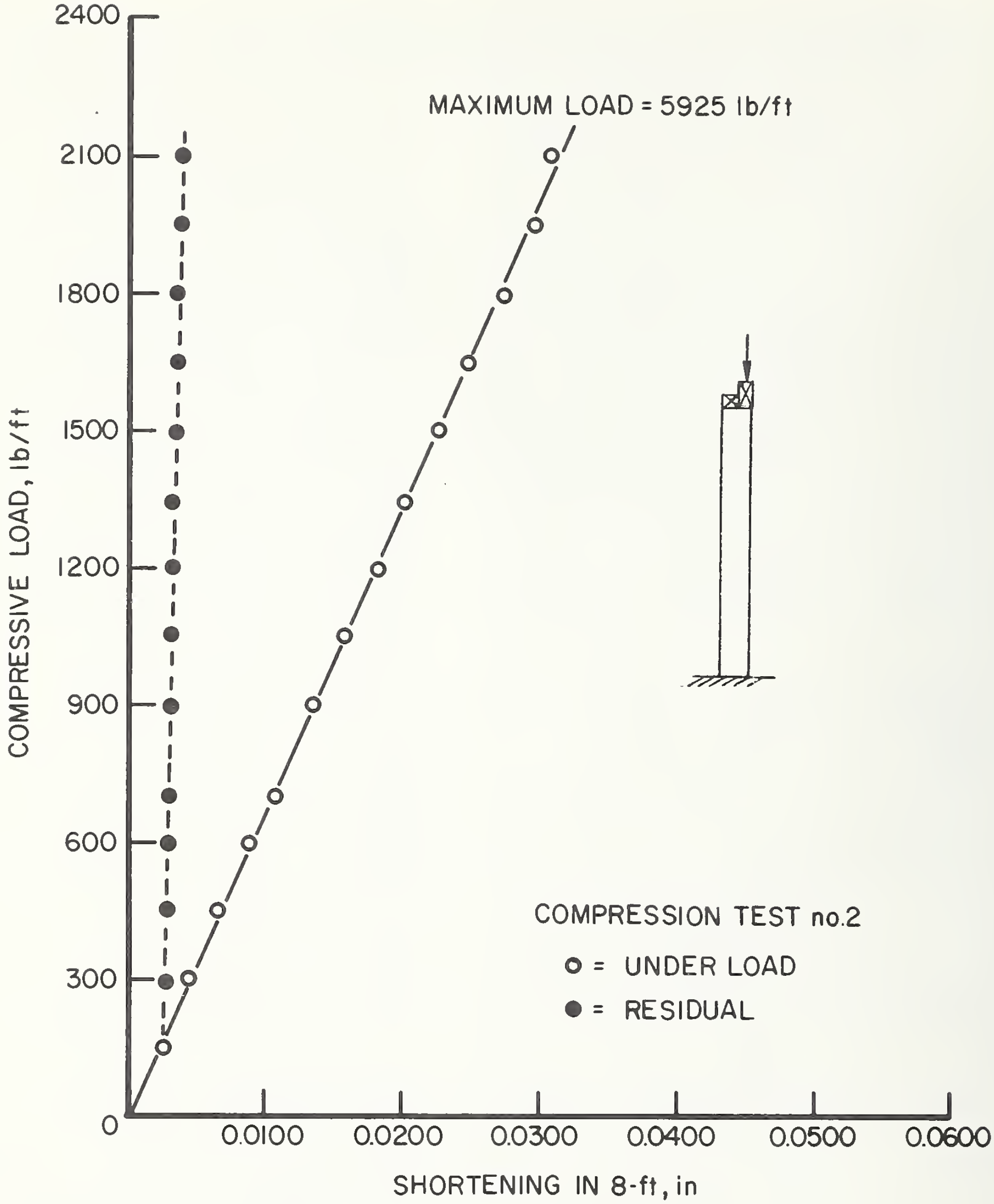

Fig. 2.3.18 Load vs. shortening for compressive test No. 2.

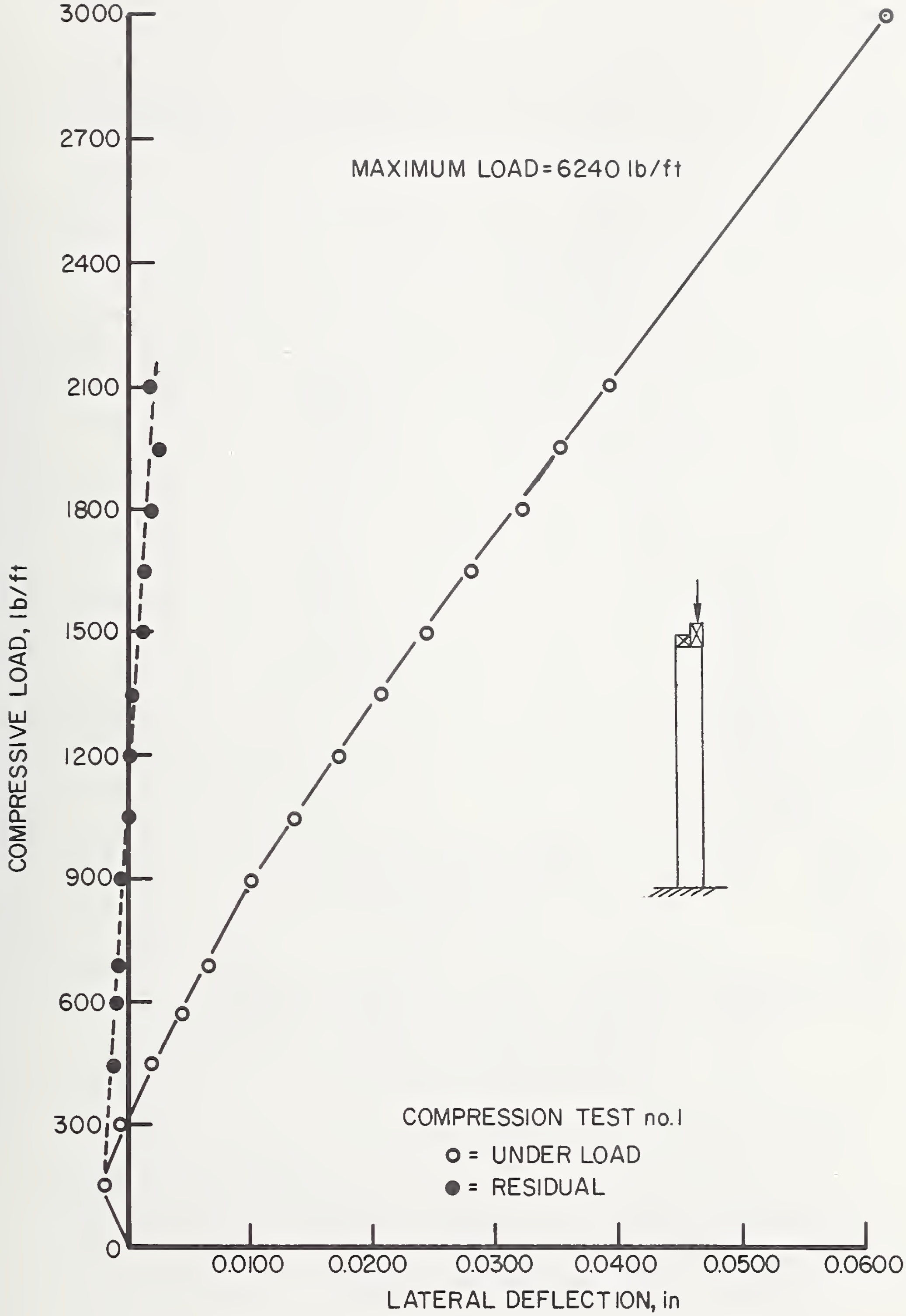

Fig. 2.3.19 Load vs. lateral deflection for compressive test No. 1.

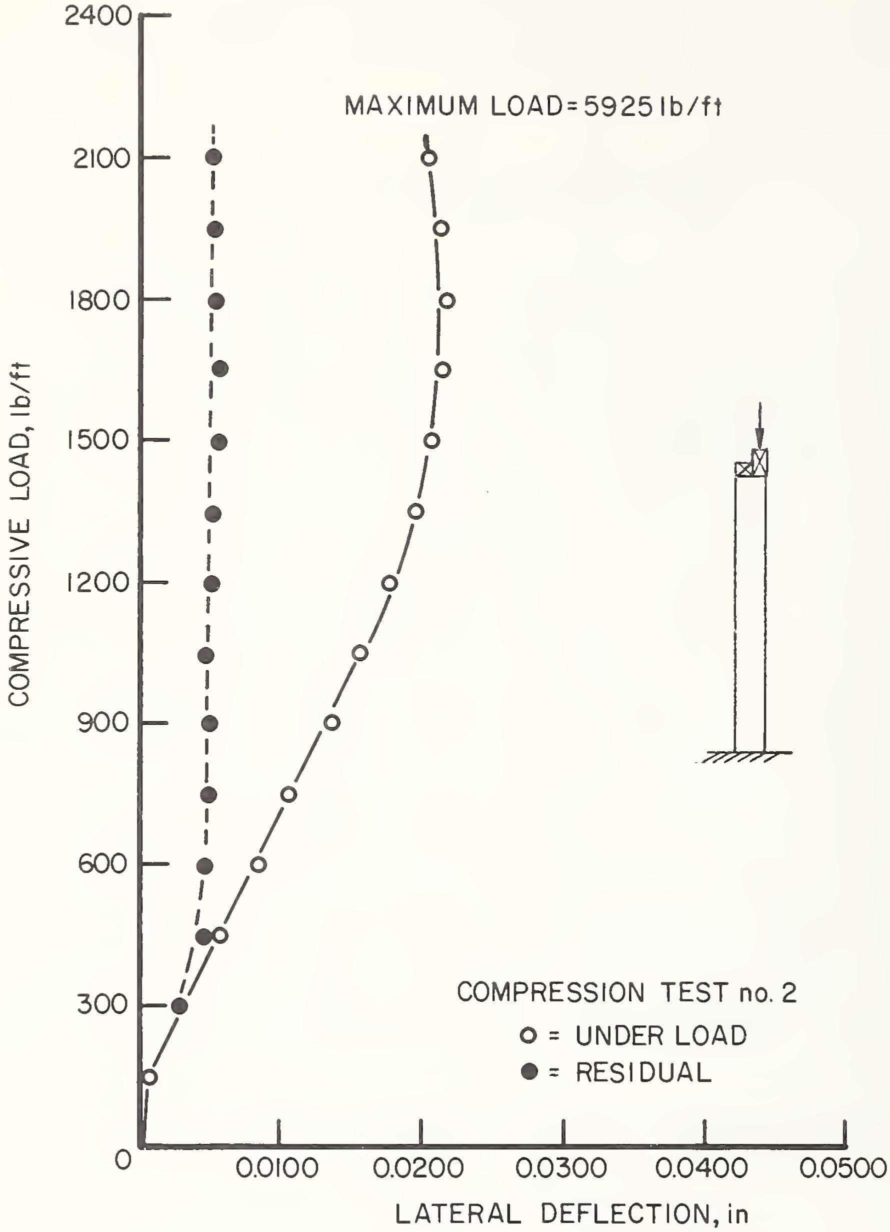

Fig. 2.3.20 Load vs. lateral deflection for compressive test No. 2.

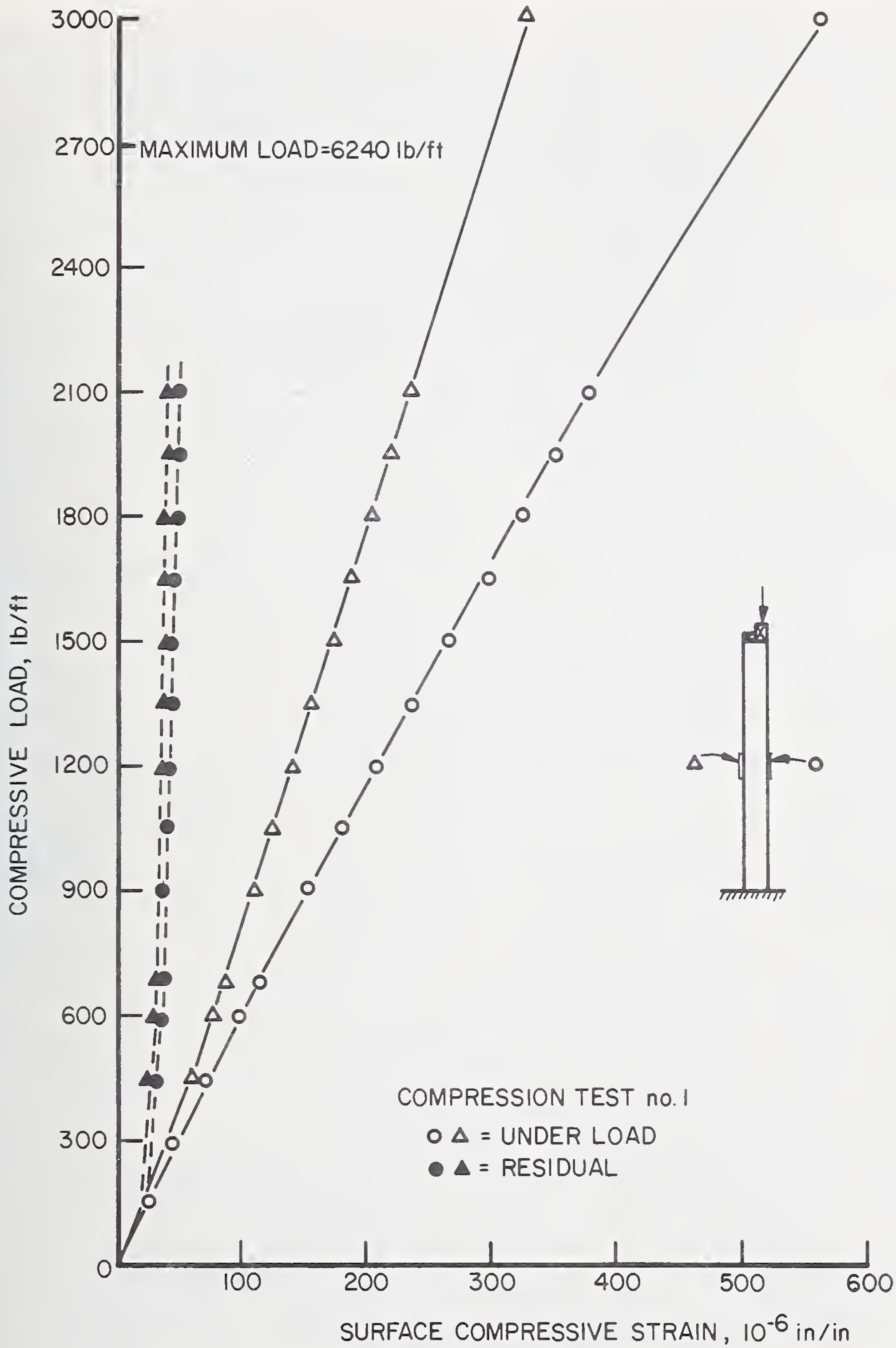

Fig. 2.3.21 Load vs. average surface strain for compressive test No. 1.

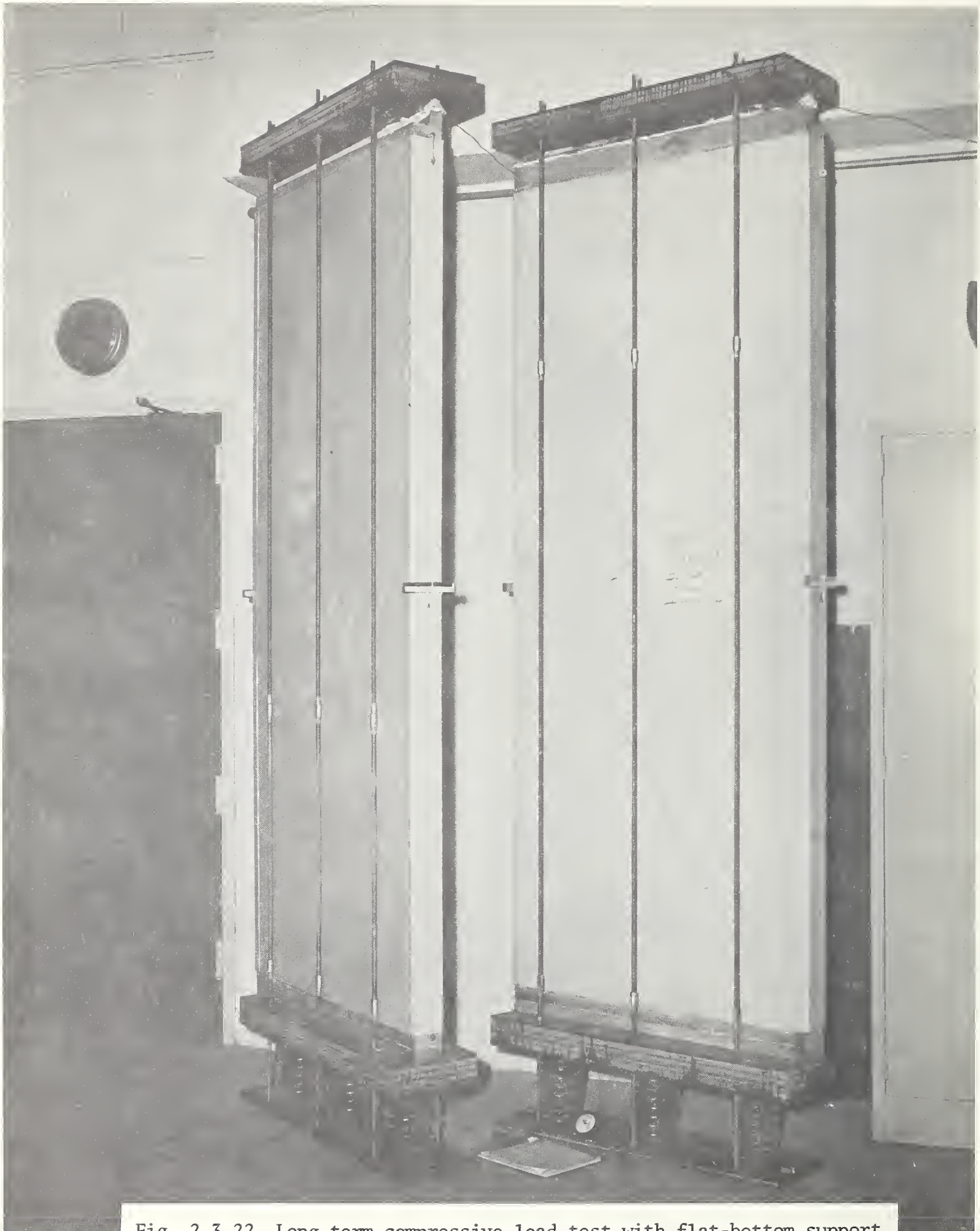

Fig. 2.3.22 Long-term compressive load test with flat-bottom support.

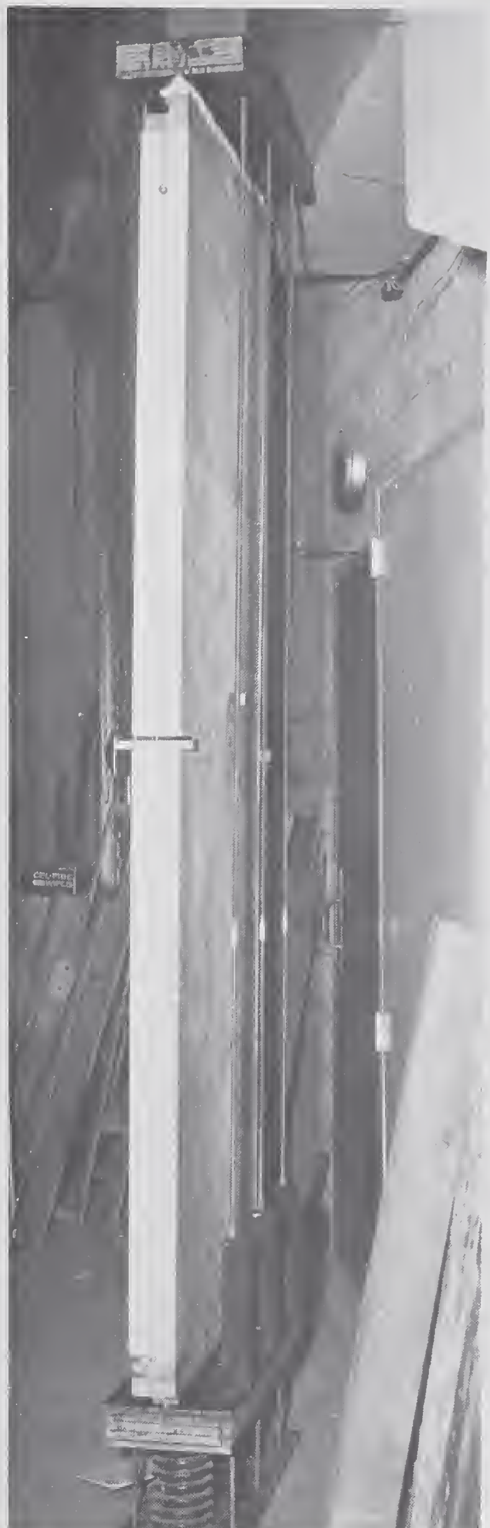

Fig. 2.3.23 Long-term compressive load test with eccentric-bottom support.

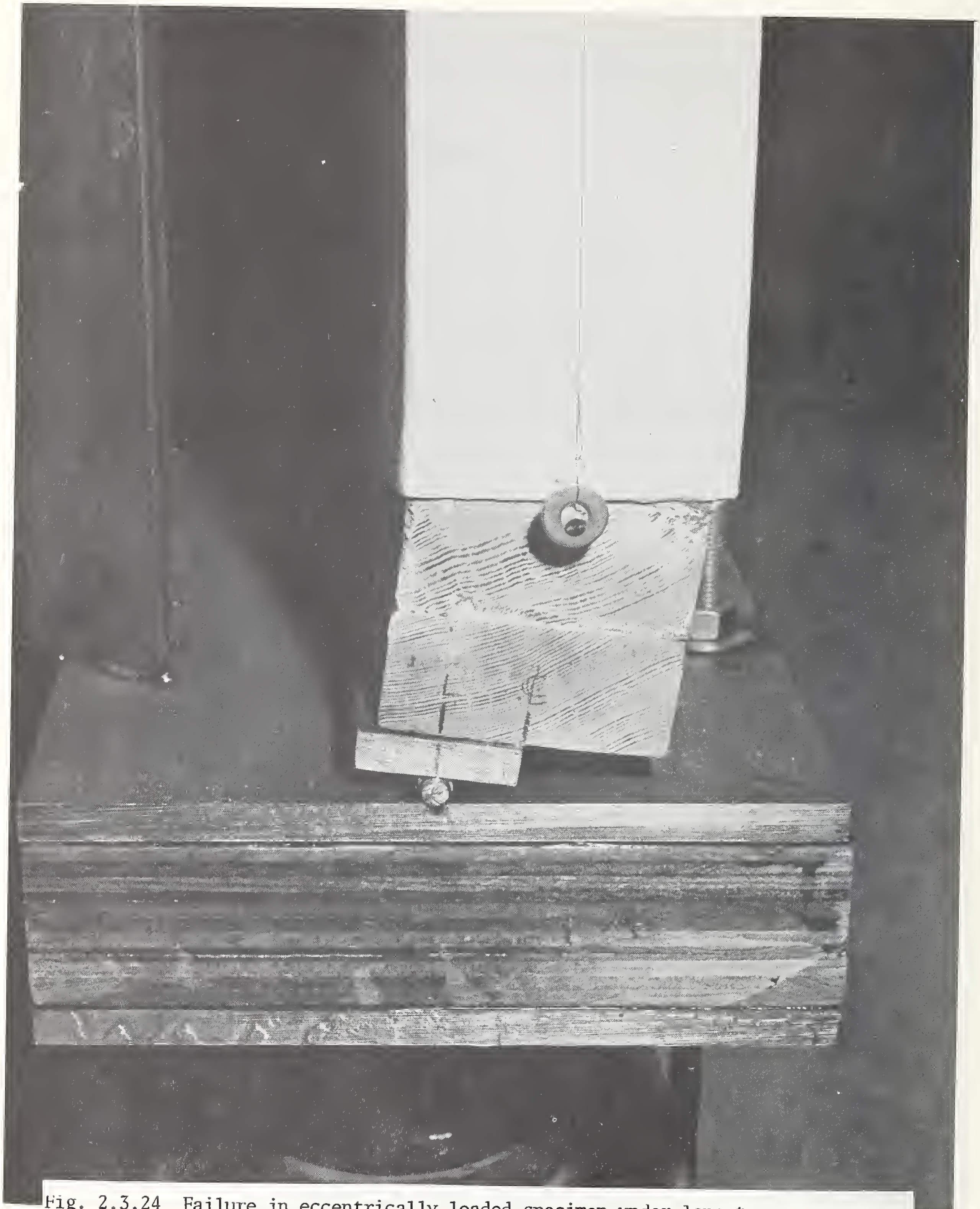

Fig. 2.3.24 Failure in eccentrically loaded specimen under long-term compressive load test.

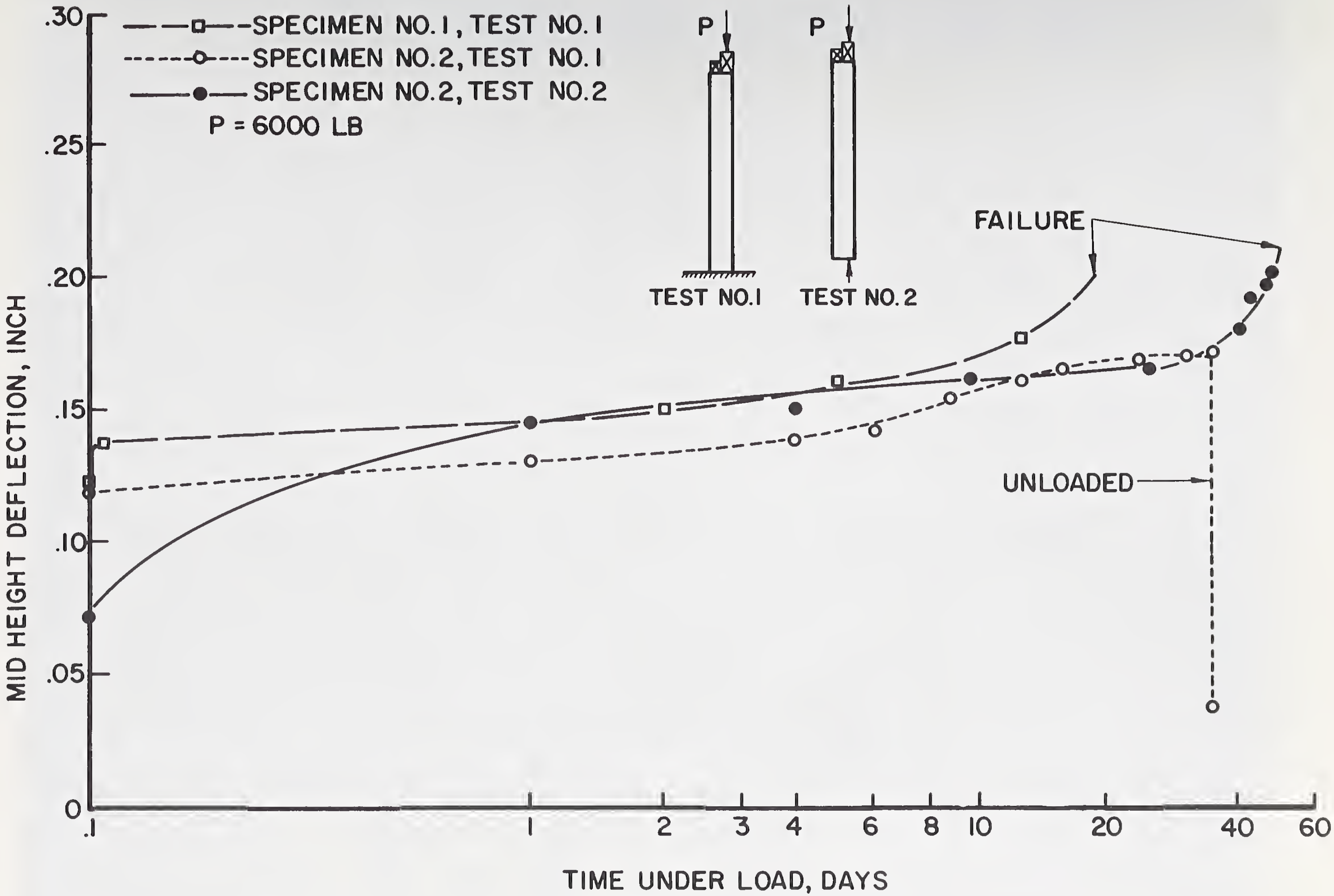

Fig. 2.3.25 Load vs. midheight deflection for the long-term compressive load test.

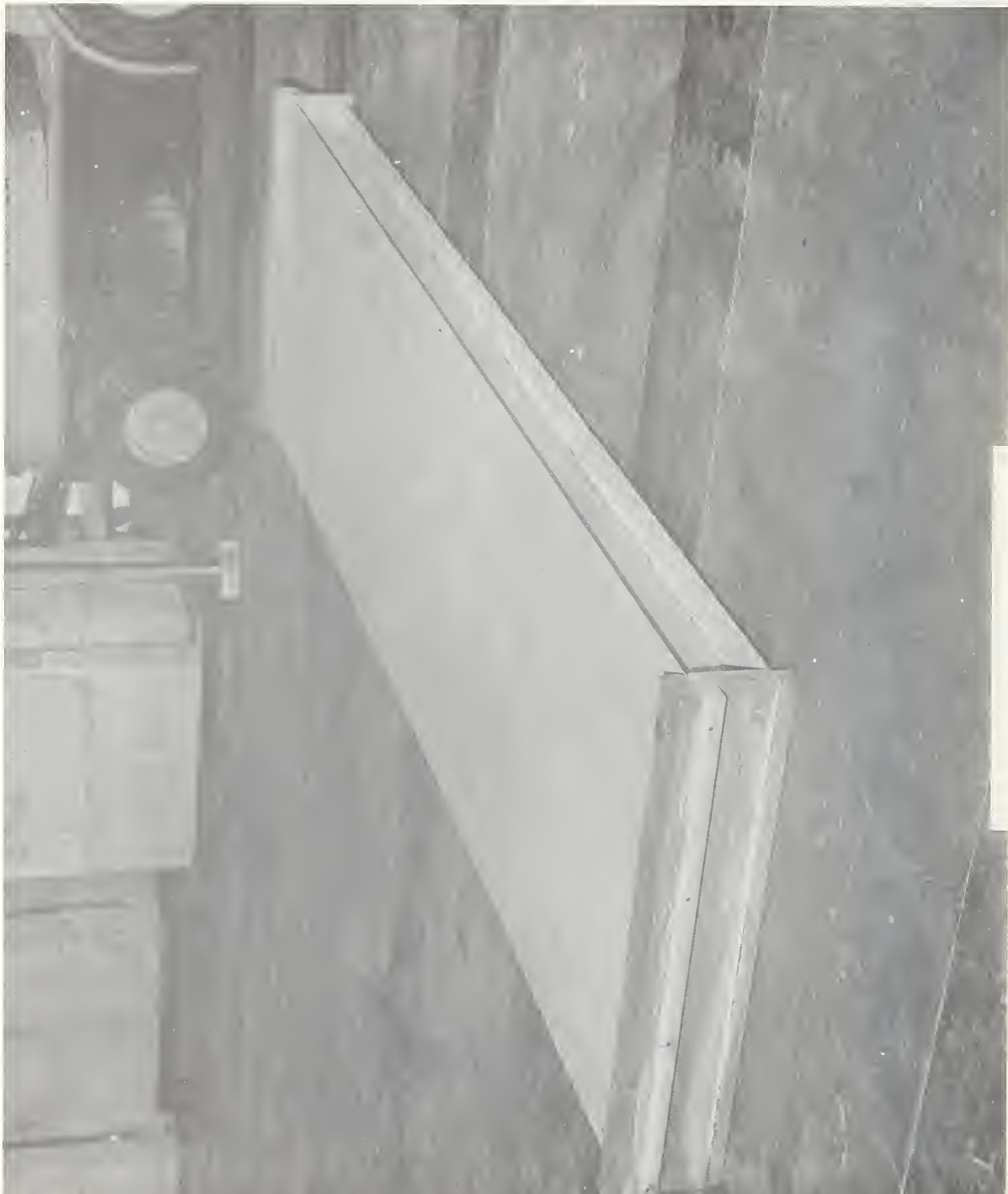

Fig. 2.4.1 Roof panel specimen.

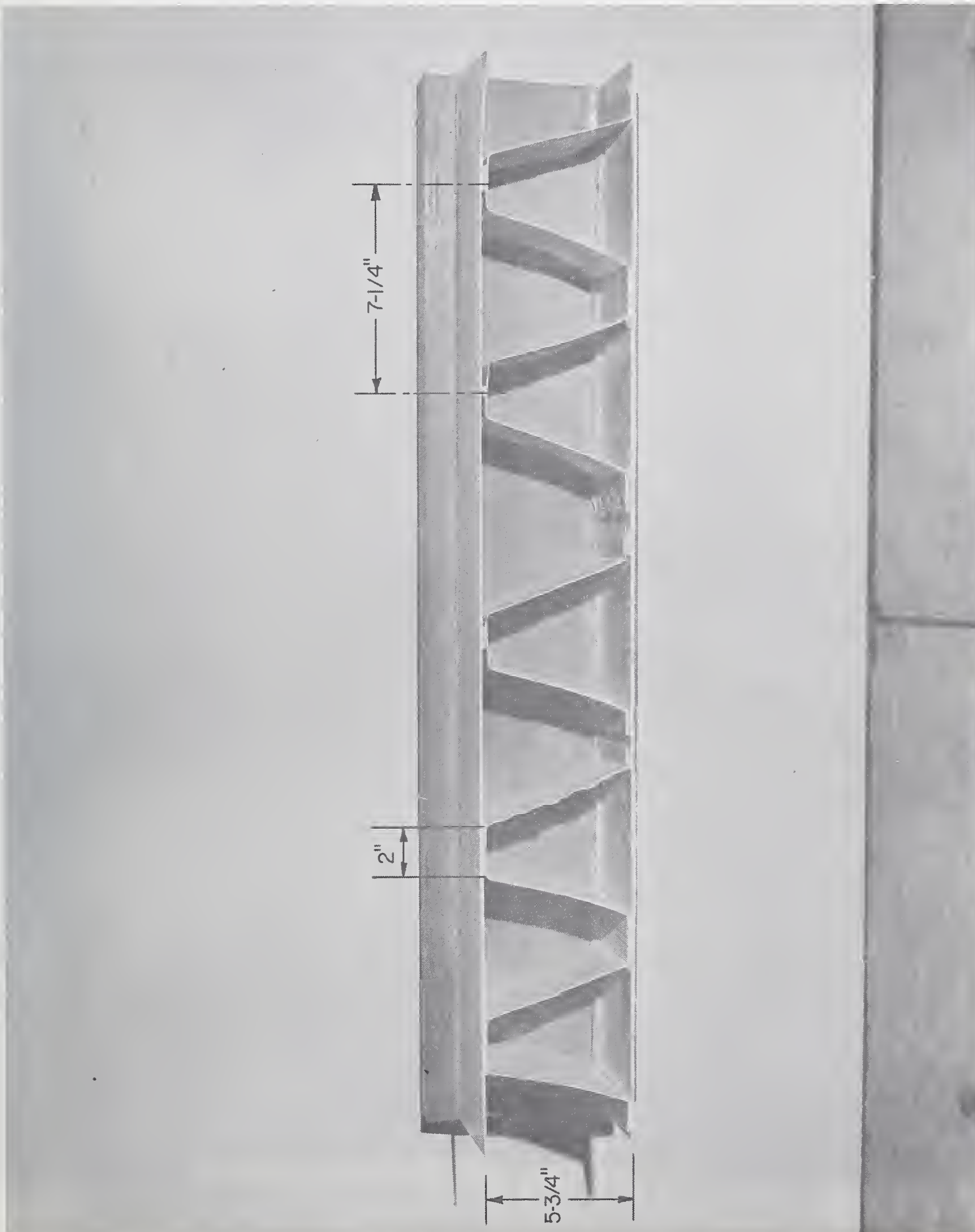

Fig. 2.4.2 Cross section of roof panel.

Fig. 2.4.3 End assembly detail of roof panel.

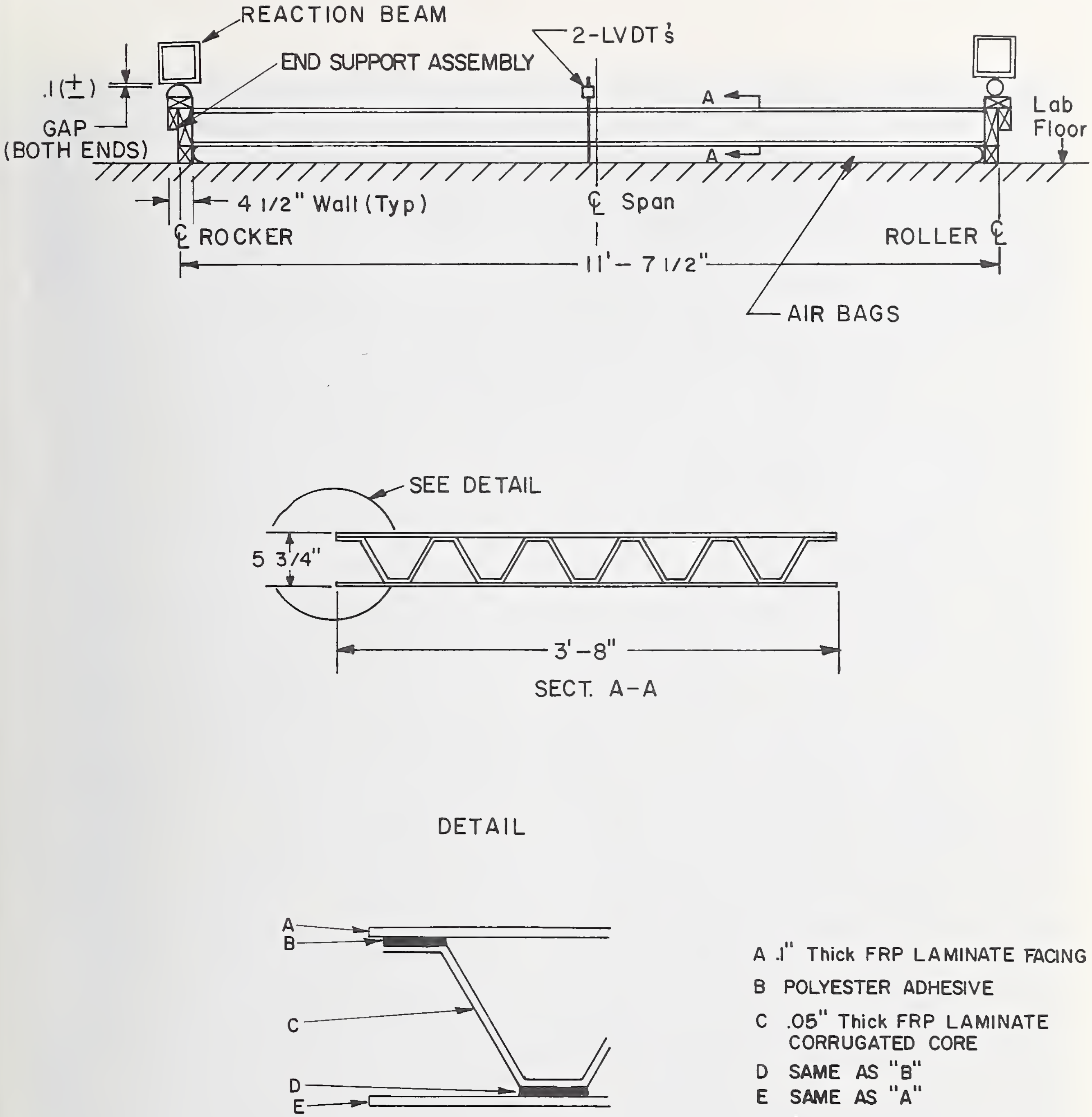

Fig. 2.4.4 Schematic of test setup for short-term flexural test on roof panel.

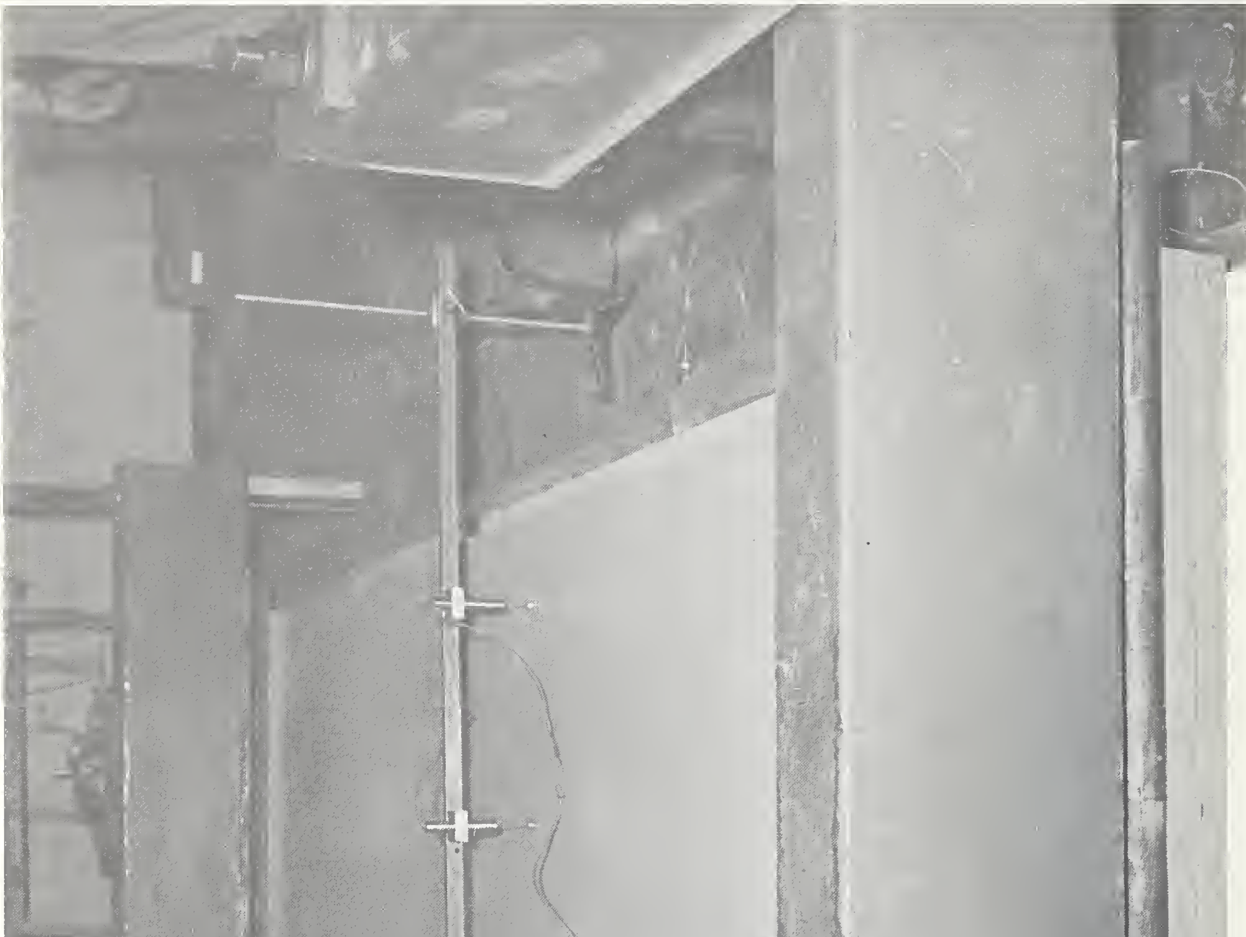

Fig. 2.4.5 Photograph of short-term flexural test on roof panel.

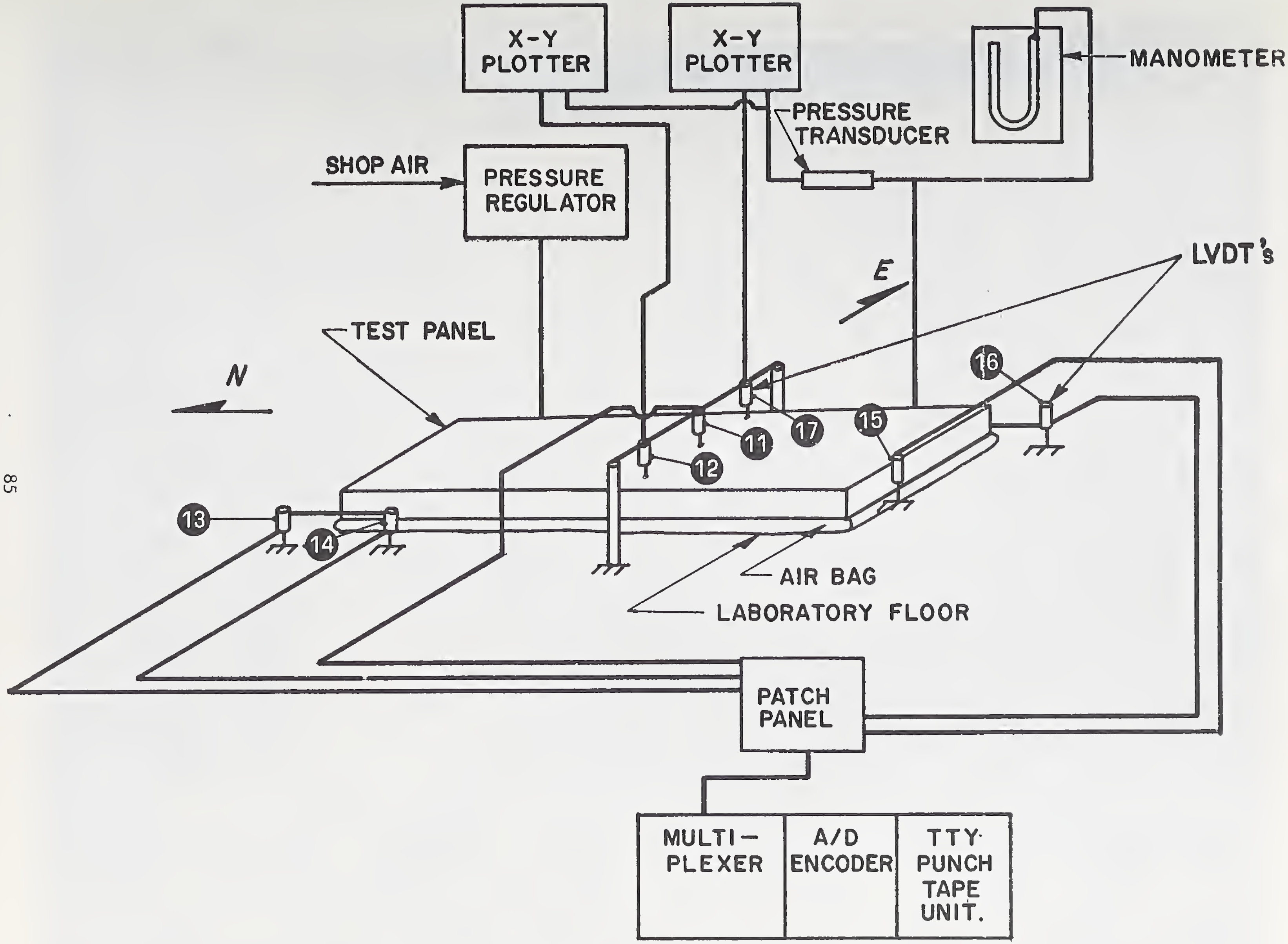

Fig. 2.4.6 Instrumentation schematic for short-term flexural test.

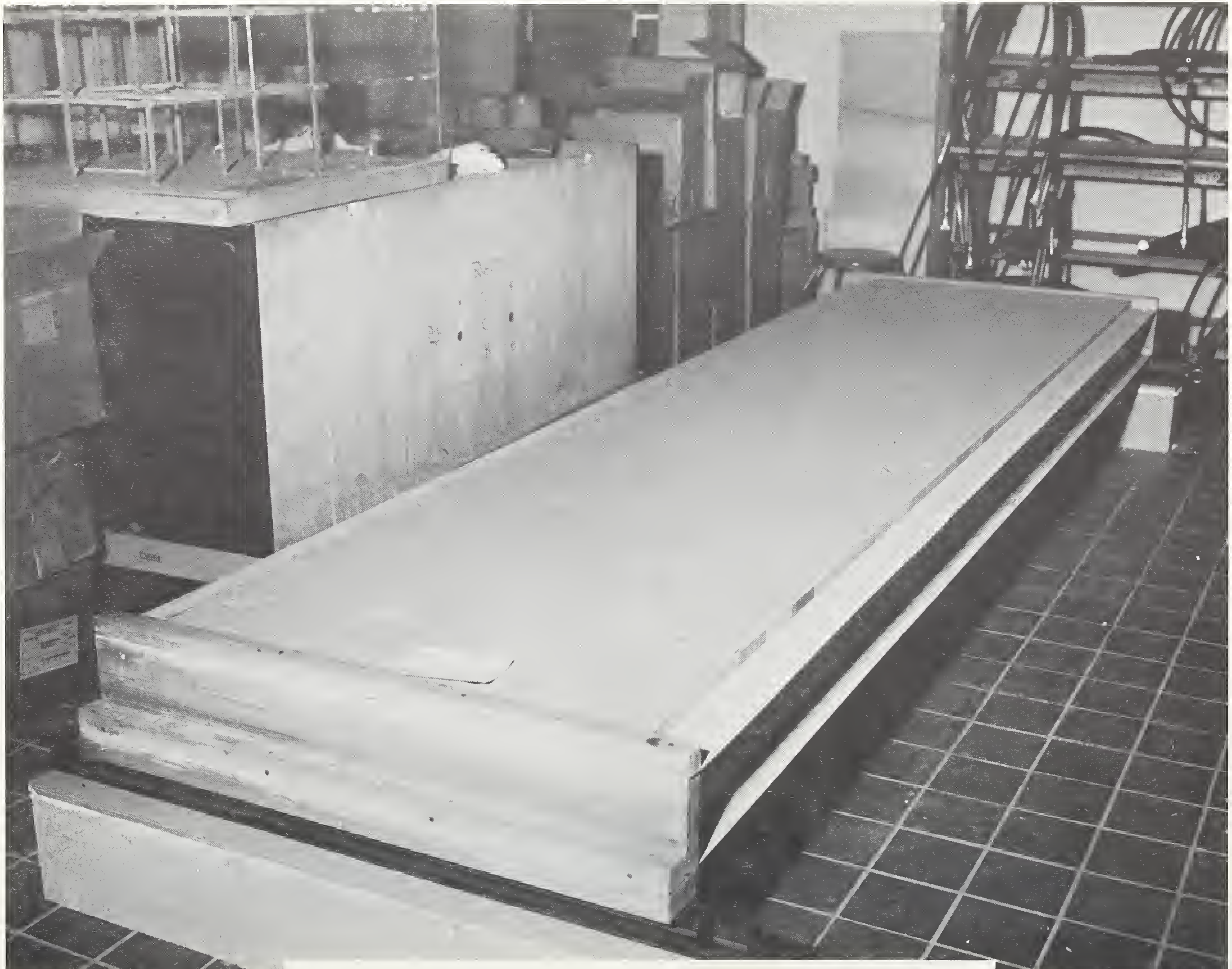

Fig. 2.4.7 Photograph of long-term (creep) sustained load test.

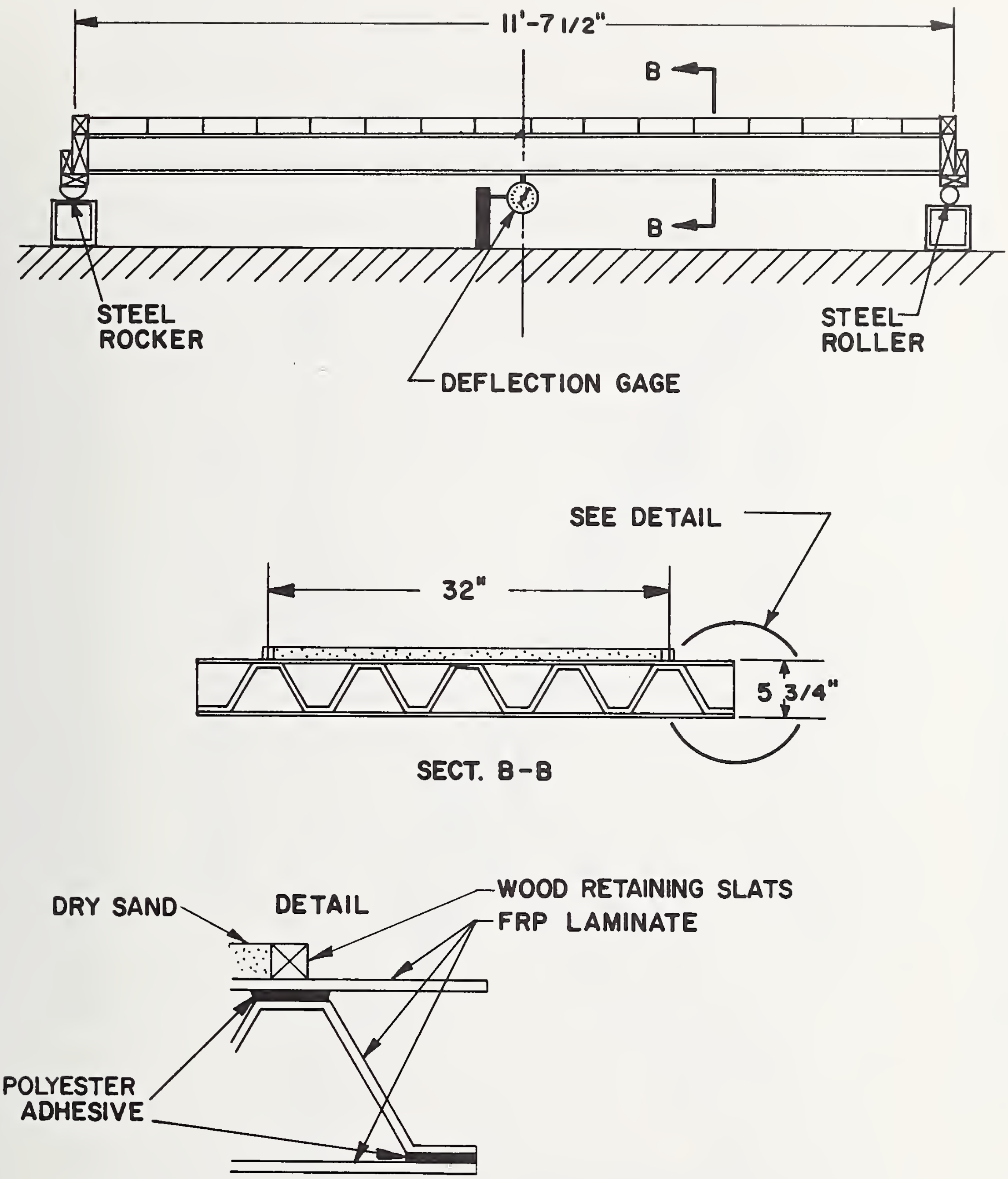

Fig. 2.4.8 Schematic of long-term (creep) sustained load test setup.

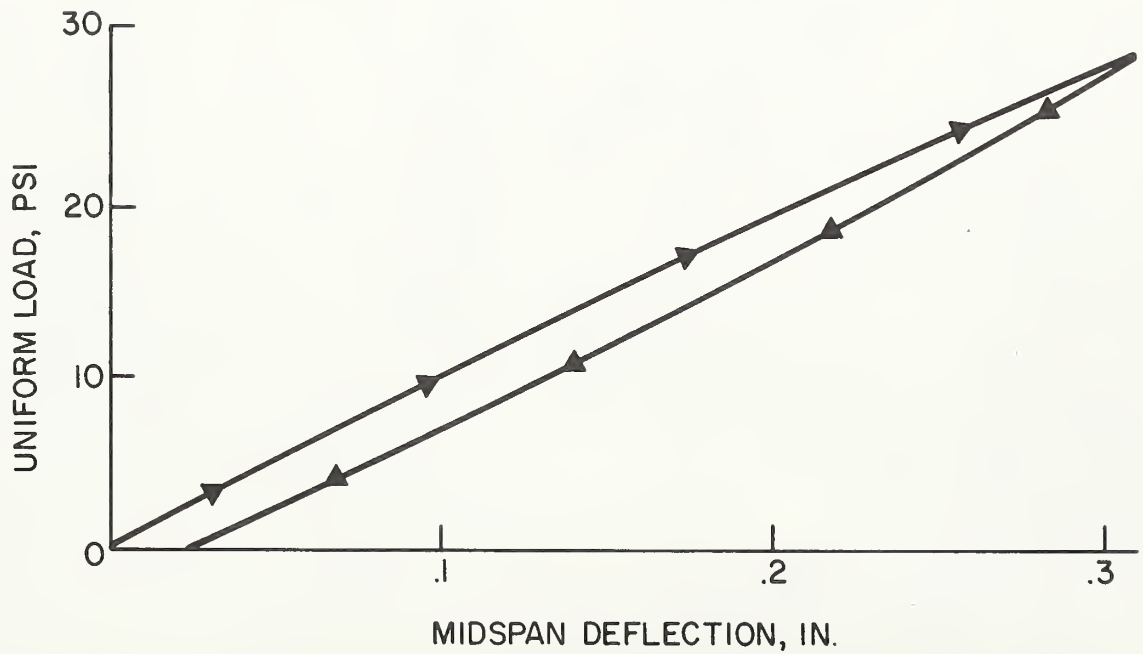

Fig. 2.4.9 Load vs. midspan deflection for one cycle of loading to 25 psf in the short-term flexural test.

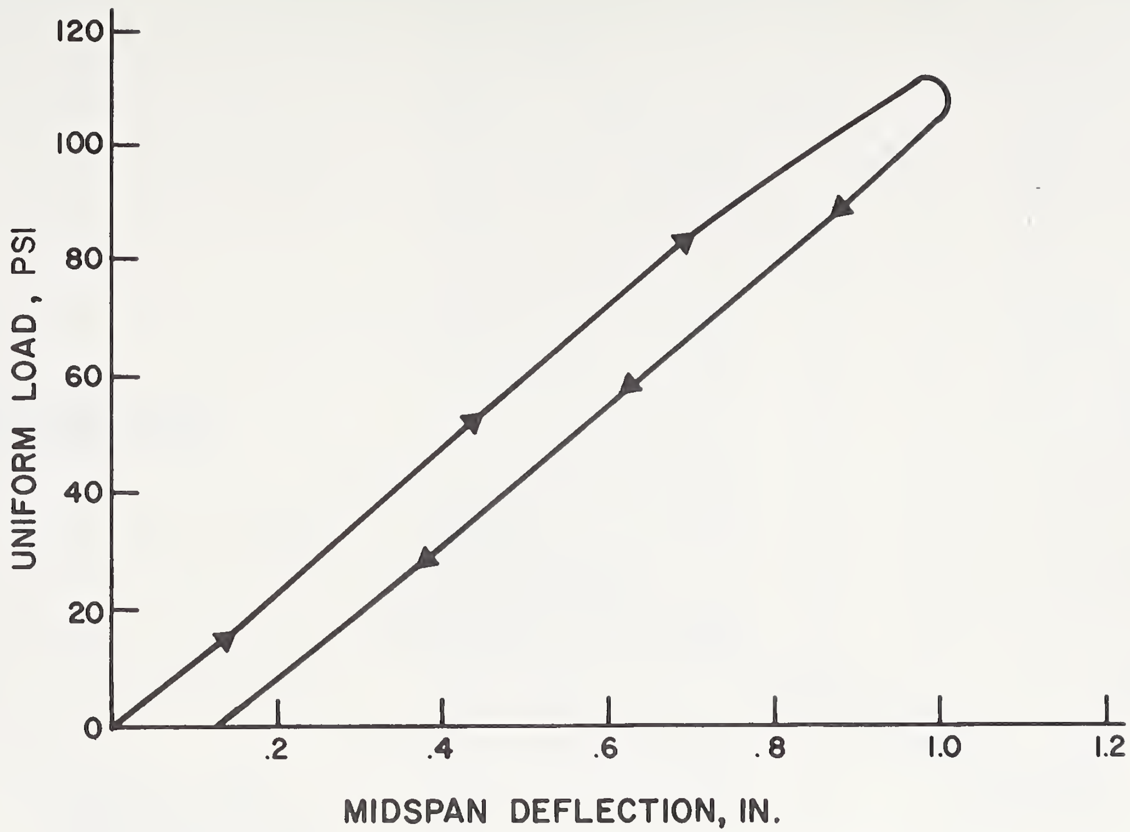

Fig. 2.4.10 Load vs. midspan deflection for one cycle of loading to 117 psf in the short-term flexural test.

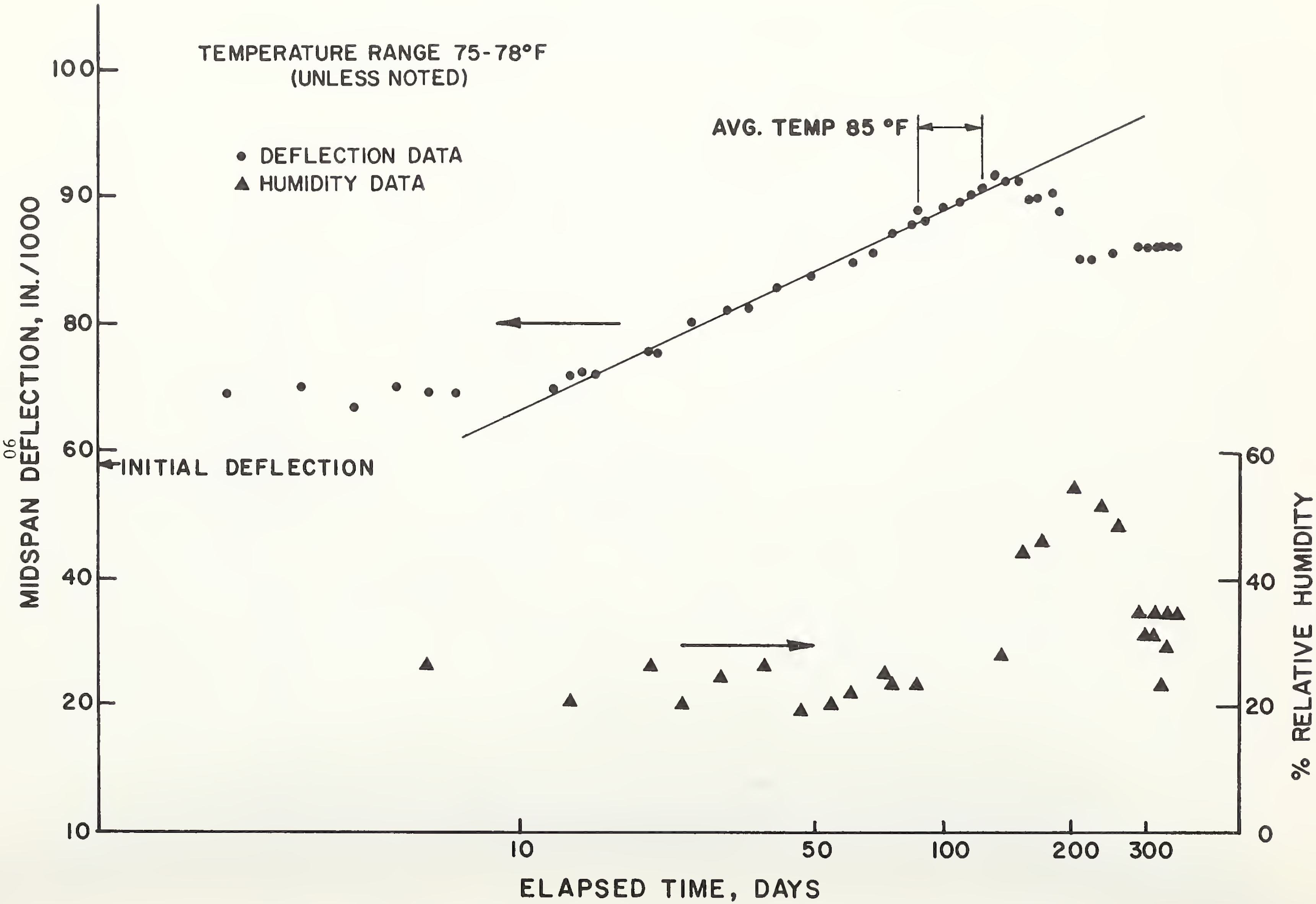

Fig. 2.4.11 Long-term test results for sustained load of 5 psf on roof panel.

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4. TITLE AND SUBTITLE Structural Tests on Housing Components of Glass Fiber Reinforced Polyester Laminate			5. Publication Date 6. Performing Organization Code
7. AUTHOR(S) T.W.REICHARD; W.E.GREENE, JR; L.E. CATTANEO; L.W. MASTERS			8. Performing Organization NBSIR 73-188
9. PERFORMING ORGANIZATION NAME AND ADDRESS NATIONAL BUREAU OF STANDARDS DEPARTMENT OF COMMERCE WASHINGTON, D.C. 20234			10. Project/Task/Work Unit No. 460 0430 11. Contract/Grant No. IAA-H-16-70
12. Sponsoring Organization Name and Address Office of Research & Technology Department of Housing and Urban Development Washington, D.C. 20410			13. Type of Report & Period Covered Final 14. Sponsoring Agency Code

15. SUPPLEMENTARY NOTES

16. ABSTRACT (A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)

This report describes a series of structural evaluation tests performed on housing components made with a glass fiber reinforced polyester (FRP) laminate. The components tested were: (1) the FRP laminate used for the facings and the corrugated core of the basic panel; (2) the adhesive bond between the facing and core; (3) typical wall panels; and (4) typical roof panels. Test data include: (1) the effect of temperature and moisture on the tensile and compressive strength of the FRP laminate; (2) the effect of temperature, accelerated aging and sustained loads on the tensile shear strength of the facing-to-core polyester adhesive bond; (3) the short-term strength of the wall panels under compressive and in-plane shear loading; (4) the long-term strength of the wall panels under sustained compressive loading; and (5) the short-term and long-term performance of the roof panels under flexural loading.

17. KEY WORDS (Alphabetical order, separated by semicolons) Adhesive bond; aging; composites; compression; flexure; glass fiber; housing system; innovations; laminate; Operation Breakthrough; racking; reinforced plastics; reinforced polyester; sustained loading; tensile shear.

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